European Association of Remote Sensing Companies

Sentinels Benefits Study (SeBS)

A Case Study

Ground Motion Monitoring in Norway

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Setting the Scene

"*Look,*" said Janne as she sat down in her living room, "*if I place this roller skate on the floor, it runs away to the other side of the room. We go uphill in the living room*", she says. "*It's fun for the kids to play at one end, because then cars and balls and other things rolls to the other end!*"

Janne and her husband Ola lived in one of the houses built by the Furuteigen's housing cooperative in Nøtterøy, south of Tønsberg. Her visitor was a friend of her husband Ola. They played hockey together and Haakon had called to pick up Ola to go to their training session. Haakon was an employee of the local council responsible for roads. "*It really does seem as though you have a problem,*" he said, "*but the house seems quite new, surely you can claim against the builders?*"

"If only it were that simple," said Janne, "*the case is being heard in the district court, but everyone denies responsibility. The housing association claims against the builders, who went bankrupt after the works were finished, the engineers say the association mis-managed the project and the insurance guarantee will only cover the builder's liability. It is a complete mess."*

"We have a similar problem with the Frodeåsen tunnel," said Haakon. "*The exit in Tønsberg is also subsiding. It was built on deep piles reaching down to the bedrock, but it seems they are not as stable as they should be."*

"Sometimes, when I am cycling, I pass by there," said Janne, "*and I have seen the damage on the cycle path. The council seem to resurface it at least once per year to fill the holes. I hit one a few months ago before it had been filled and had to have my front wheel reset."*

Ola came into the room at that point. "*Are you talking about the subsidence?*" he said *"I heard from our goalkeeper that the new leisure centre is having problems as well. They are building it down by the water and it seems that the piles have penetrated a deep clay layer and now the whole site seems unstable. They have had to stop work whilst they look at the problem and how to fix it. They say the cost of the works may double as a result. It seems as though the whole county is sinking!"*

Haakon looked thoughtful, "*rework of the tunnel is costing us millions,*" he said. "*If we had known about the potential subsidence when we were doing the design, I feel sure we could have avoided this. Anyway, if we don't leave now we shall be late and have to pay for the drinks later."*

"Have a good evening," said Janne as the two men left for their sport.

It was three weeks later, and Haakon had again arrived to pick up Ola. As he entered, he said to Janne, *"I have some news about the subsidence. I was sent a mail from Oslo, the Statens vegvesen who were responsible for the original tunnel design wrote to me telling me about a new service from the NGU. They are producing a map using satellite images. I don't know how it is possible, but these images show motion of the ground to a few millimetres of accuracy. Since it is paid for by the Norwegian government it is free for everyone to use."*

"*Can you show me,*" asked Janne.

"*Sure I can, do you have a computer*? Asked Haakon.

Janne led him through to her study as Ola joined them. Haakon sat down and quickly tapped a URL into the browser. A strange picture appeared covered with green dots. "*This is Oslo,*" said Haakon as he typed Tønsberg into the search box. As the new image appeared, he explained that the green dots were measurement points on the ground and as long as they are green the ground is stable. If the dots are coloured yellow through to red, it indicates some motion over the year between the satellite images. "*Don't ask me to explain more,*" he joked to Janne and Ola, *"it's rocket science as far as I'm concerned., but the results are quite incredible."*

They looked at the picture of Tønsberg which was covered in red and yellow dots, *"our tunnel is here,"* said Haakon, "*right on the edge of the area of coloured dots. We would never have guessed that the whole town of Tønsberg is moving. Mostly it is not a problem, only on the edges can it lead to cracks as is the case for our tunnel and for the new leisure centre."*

He shifted the image to show Nøtterøy, "look, here is your house and sure enough we have a small cluster of coloured dots. "*It shows that your house and the ones around you are indeed moving. It may help to understand now but clearly, had this map been available before it was built, like our tunnel, different methods could have been used to prevent these problems."*

"This service may not help you or me now, but it should help many others in Norway avoid similar situations in the future," he finished.

"Aren't satellites amazing," said Ola, "*I would never have guessed that they could measure with such accuracy. If only I could control an ice-puck so precisely, we would be top of the league!"* and the two men left for their match.

Setting the Scene provides a short anecdotal introduction to each case. This story is entirely imaginary, although realistic based on our knowledge gained through the case interviews. The places are real, although the characters, the conversation and the situation are entirely fictional. See also report by NRK – Norwegian TV service. [1]

[1] Internal note translation of NRK article.

Executive Summary

In 2014, the Norwegian Space Agency (NSA) and the Norwegian Geological Survey (NGU) decided to create a new mapping service showing ground motion covering the whole of Norway. The first map was released in 2018 and has been updated each year since. Generated once per year using data from Sentinel-1, it allows users to detect where subsidence is occurring. The map is available on-line and is a free-and-open dataset as befits data coming from a national, publicly funded agency.

The Norwegian Public Roads Administration (NPRA) became one of the main users of the service and is the focus of our analysis. We discuss four projects where the service has been or is being, used to help with road construction projects. In the case of Tønsberg, where a tunnel has experienced many years of problems, engineers were at a loss as to why subsidence was occurring. Now the mystery is solved – thanks to the new service – which shows that rather than being a local problem, it extends over the whole town. This scale of survey measurements would not be possible using traditional methods, and hence the service is providing unique information. Had the service been available when the tunnel was designed and built (in 2004-2008), considerable savings would have been made by avoiding costly remedial work in recent years. Knowing the extent, scale, and degree of ground motion during the planning and design phases of projects can lead to more appropriate designs and avoid costly repairs later.

In another project, corner reflectors were placed on newly laid ballast for the foundations of a new bridge across Sifjord. The very precise measurements coming from regular measurements of the reflectors, made possible by regular passes of the Sentinel-1 satellites, allowed the engineers to see the settlement of the rock ballast to millimetre accuracy and hence to judge with more confidence when settlement had reached a level where the next phase of the work should start. In such remote areas as Sifjord InSAR can give a better foundation for decisions during building projects.

Larger scale projects are also experiencing the benefits. In Fredrikstad, a new railway link will also require new road access. The cost of the project has increased considerably due to the engineering of measures necessary to reduce subsidence. This is expensive, and studies are still on-going as to the best solution to adopt. The ability to measure and monitor the current and historical ground motion can save millions of Euros by enabling a better design approach.

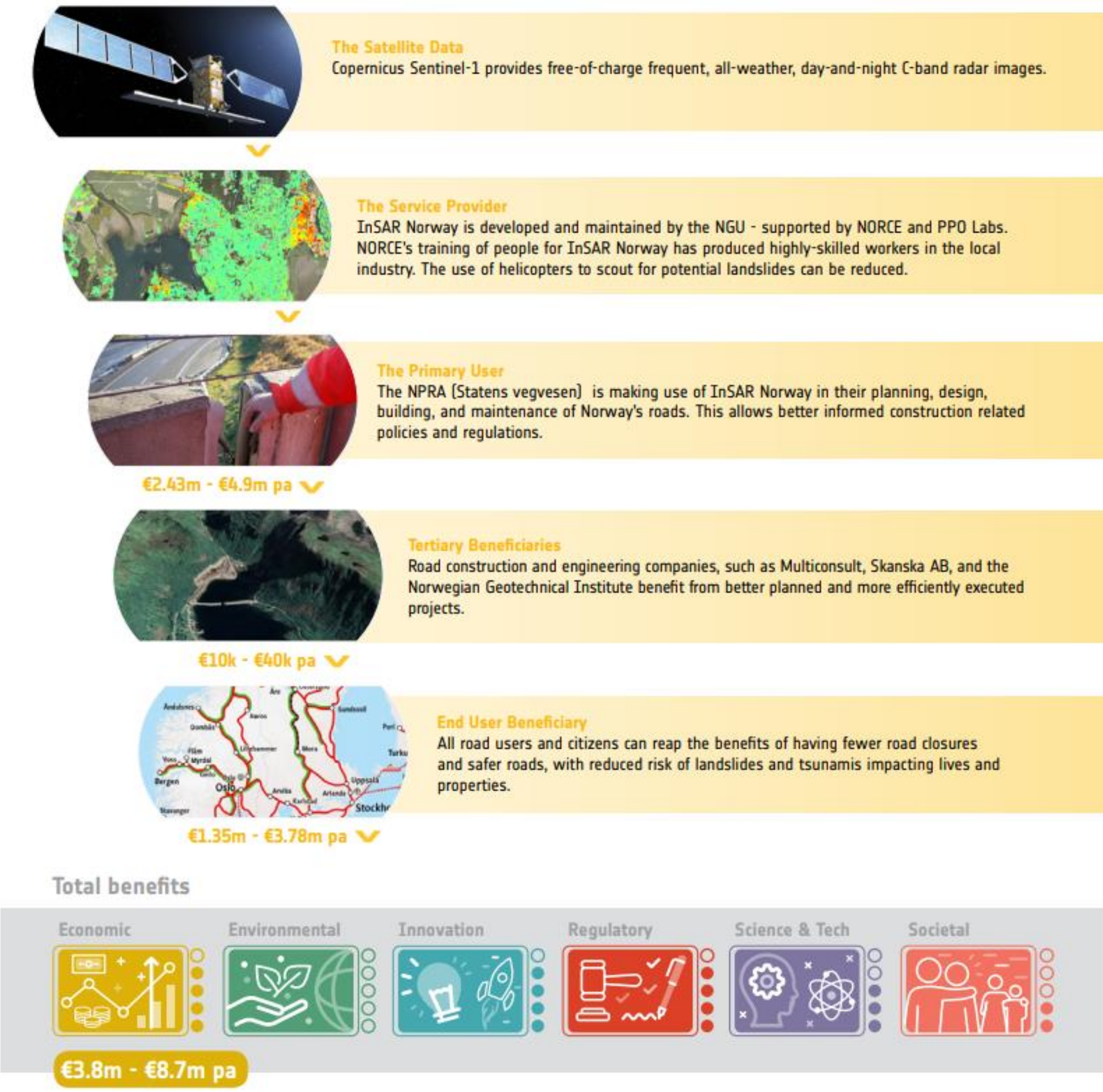
Finally, in the centre of Oslo, a major redevelopment along the waterfront and beside the main railway station is finding unusual ground settlements and subsidence which is affecting its construction. Gathering a wider view using the InSAR generated ground motion maps allows a synoptic view to be taken. These four projects illustrate the savings which can be made in the construction and management of roads in Norway.

One of these "other ways" is the monitoring of mountainsides for major rockslides. The Norwegian Water Resources and Energy Directorate (NVE) have a responsibility to deal with threats and emergencies coming from natural hazards. One such hazard is the risk from landslides, and tsunamis in the narrow fjords caused by rockslides. Some in the past have been so severe as to cause flooding and loss of life in villages along the coast or lakes. The Geological Survey of Norway

(NGU) supports the NVE by mapping, at a national scale, to identify and characterize unstable mountainsides. In the past, this involved flying a helicopter for several weeks to observe unstable mountainsides. The ground motion map was developed as a tool to help identify critical masses more easily and to help understand if a threat is imminent.

A further service that is based on Sentinel-1 images is being used to detect snow avalanches. Apart from the risk to vehicles and infrastructure, avalanches can block roads and cut communications between affected areas. Road users benefit from being aware of the avalanche threats as do the construction crews who are sent to clear the road afterwards.

As a country frequently covered by cloud, Norway is finding ways to benefit enormously from the Copernicus Sentinel system, and particularly the Synthetic Aperture Radar carried on Sentinel-1. In our analysis, we estimate an economic benefit of between €3.8m and €8.7m per year for the management of road infrastructure in Norway alone.



1 Introduction & Scope

1.1 The Context of this study

The analysis of the case study *'Ground Motion Monitoring in Norway"* is carried out in the context of the 'The Sentinel Economic Benefits Study' (SeBS). This 4-year study is looking to develop cases showing how EO-derived products based on data generated by one or more Sentinel satellites deliver value to society and citizens. The Sentinel satellites form a crucial part of EU's Copernicus Programme, providing space-based observations on a full, free and open basis. Data coming from the Sentinels – together with other data collected by contributing missions and ground, sea or airborne instruments – is used to support key economic or societal areas such as agriculture, insurance, disaster management, climate change monitoring, etc. Sentinel data are thus a key component of the Copernicus Services, and a crucial source used by companies to deliver products and services helping different users across the Globe.

1.2 What is the Case all about?

In 2014, it was decided to establish a Norway-wide ground motion mapping service (InSAR Norway[2]) using the free data coming from Sentinel-1. This service, which is made freely available under the open data policy principles, is used by many different actors in Norway. Hence there are many potential use-cases which will be briefly discussed in the report.

The primary use-case in this report is based on the use of the maps to support road construction and maintenance; where the primary user is Statens Vegvesen, also called the Norwegian Public Roads Administration (NPRA). Road construction, whilst a continuous process when viewed at a national level, consists of a series of many projects. The scale of these projects differs enormously, as does the nature of the risk incurred. The case is analysed by considering the range and variable nature of the road construction projects - including their scale and degree of risk. Some specific cases are used to explain the nature of the analysis and to consider the boundaries to the assumptions used.

The NPRA use the basic ground motion maps throughout the lifecycle of road projects. During the planning process, it is used to identify areas at risk and to focus on more detailed surveys. During the construction phase, the maps are used to monitor if the works have had unexpected impacts on the local environment and particularly giving rise to a risk to housing or commercial developments. During the operations and maintenance phase, the maps can be used to identify any longer-term impacts and to signal threats to the road due to landslides.

Others in Norway also use the ground motion map in their daily work. The Geological Survey of Norway, which was at the origin of the project, use the maps to identify potential landslides into fjords which may threaten to flood local settlements. The Norwegian Geotechnical Institute (a

[2] InSAR Norway from the Geological Survey of Norway (NGU)

private foundation) use the maps to identify natural hazards and risks; working with the Norwegian Water Resources and Energy Directorate, Skanska, an engineering company, use the maps to monitor the impacts of their works so avoiding litigation. All these will be discussed alongside the core use-case.

During our interviews, we found out that the NPRA, the primary user is also making use of another service which is based on the imagery coming from Sentinel-1. Since the case is about the benefits of Sentinels for road management in Norway, we considered that this second service relating to avalanche forecasting should also be recognized in the case report.

In a second twist, the Geological Survey of Norway (NGU) which is a co-supplier of the ground motion map, is also a user of this map; effectively creating a second value chain. We decided not to focus on this value-chain heavily, but that it should at least be recognized. Hence, in divergence with other cases, we also describe this second value-chain stemming from the ground motion service, which is focused on detecting and understanding landslides.

1.3 How does this case relate to others?

The use of InSAR to monitor ground motion has been the subject of a previous case "Infrastructure Monitoring in the Netherlands" and another looking at the management of roads in Italy. It will surely feature in others. In the Netherlands case, the use-case was the monitoring of ground motion linked to the management of gas pipelines. As the project evolves, we anticipate that a portfolio of InSAR related cases will be established.

The variety of applications of InSAR can lead to a significant portfolio of cases. Its application is very broad and still developing as it becomes wider-known and better understood. At the time of writing, two other cases (in Italy and Spain) based on the use of InSAR are also being completed, of which one is also looking at a use-case around roads.

While the road transport sector may have other ways to benefit from satellite EO, the use of InSAR is, at least currently, seen as the main tool from which the actors can benefit. The ability to measure small motions in the ground surface, or even below ground, on a sustainable and relatively low-cost basis, is becoming recognised as a powerful tool. Many of the applications do require relatively frequent updates to the maps and a higher spatial resolution on the ground than can be achieved using the free Sentinel-1 data. Hence, it is common that free services are used to trigger more detailed analysis using commercial, higher resolution satellite data.

As we develop the portfolio of cases based on InSAR, the wider picture will be considered to draw conclusions between the different types of applications (or use-cases).

1.4 More About the Study

Each case study analysed in SeBS focuses on products and services that use data coming from Sentinel satellites, measuring the impact of that product or service throughout the value chain. The starting point is the primary user of the satellite data, followed by a step-by-step analysis whereby the operations of beneficiaries in each subsequent link of the value chain are analysed, all the way down to citizens and society.

In this process, the main aim is to understand and demonstrate the value which is generated using satellite-based Earth Observations (EO) and particularly the data coming from the Copernicus Sentinel satellites. Each case study thus underlines the causal relationship between the use of Copernicus Sentinel satellite data and benefits resulting from their use, including increased productivity, more efficient and environmentally friendly operations, economic gains and improved quality of life, among others. The evaluated and demonstrated benefits can be used by:

- **Decision-makers**: Having access to a portfolio of concrete cases where the benefits from the operational use of Sentinel data in decision making are clearly articulated, helps decision-makers not only to justify future investments but also to direct them towards areas that most matter in their country or organisation.
- **Users:** Moving beyond a vague idea of how EO services can support more effective operations requires a concrete understanding of the benefits they can actually bring in similar cases. In this regard, it is both numbers and stories that can resonate with users and attract them to explore further or deeper uses of EO in their operational activities.
- **Service providers:** Solid argumentation around the economic and environmental benefits stemming from the use of EO, coupled with powerful storytelling, can become an effective marketing tool for service providers seeking to promote their solutions and for EARSC to promote the sector.

In the framework of this project, case studies will be developed with reports to be published on each one. The study has started in March 2017 and will end in mid-2021.

1.5 Acknowledgements

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Jan Petter Pedersen (Kongsberg Satellite Services - KSAT)

2 The Road Network in Norway

In this chapter, the management of the road network in Norway is discussed along with the various challenges that are facing its development and maintenance. Examples are given of some high-profile cases which show how ground motion maps can help in the management task by highlighting the complexities involved, and in some cases, the failures to understand the ground conditions before and during construction.

2.1 Development of the road network

As a land of dramatic fjords, sheer rock cliffs, sweeping valleys, and snow-capped mountains, the road network stretching across Norway's breath-taking landscape is a vital piece of infrastructure connecting villages, cities, and regions previously isolated from one another. It is regarded as a crucial lifeline for both the citizens and the economy of this beautiful Nordic country. The roads here are indeed impressive, from the monumental bridges connecting remote islands all along the Norwegian coast to the many tunnel networks which pass through mountain rock. Norway has pioneered many road infrastructure triumphs, such as the Eiksund tunnel, which, at a depth of 287 metres below sea level, holds the record for the world's deepest, undersea tunnel. Norway also boasts the world's longest road tunnel, the Laerdal tunnel, which spans an amazing 24.5 kilometres[3].

With its seemingly endless mountainous terrain, Norway is certainly not the easiest place in the world to build and maintain a road network. Apart from the difficult construction conditions, the constant threat of landslides and avalanches is something the road authorities must take into account for planning and design and deal with daily. Ground motion can lead to devastating consequences, destroying roads, triggering tsunamis within fjords, and ultimately injuring and killing citizens. Norway's road authorities must remain extremely vigilant when it comes to identifying, classifying, and monitoring potential risks during both the planning and operations phases.

The key risks, and those we consider in this case, result from ground motion, whether due to rapid events, notably landslides or avalanches, which threaten to cut-off roads or slow events such as subsidence, which may provoke a landslide or catastrophic failure of the road. Subsidence can also lead to significant problems during the construction of the roads and which even have been triggered by the construction works. In some areas, for example in Oslo, deep moraines may overlay the bedrock, and without adequate piling can lead to subsequent problems (see Figure 2-3).

In winter months, when the snow is lying deep, there is a risk of avalanches posing an immediate threat to passing vehicles but more likely causing delays whilst roads are cleared. Being aware of the location of the threat and even more when avalanches occur helps the road management authorities to react better.

[3] Facts about Road Transport in Norway, Kjell Bjørvig. Deputy Director General, NPRA

2.2 Geological considerations

The landscape of Norway is defined by its mountains and fjords, both of which present barriers to direct road links and a simple road network. As a result, Norway is one of the leading exponents of tunnelling with extensive experience of road construction in difficult conditions.

Norway is a landscape created from ancient mountain ranges that have been ravaged by water, wind, and particularly ice over millions of years. Although it has been quite some time since the tectonic collisions that created Norway's mountains took place, tectonic processes are still active in Norway, with small to medium earthquakes occurring all over the Fennoscandia region to this day[4]. In a country where the stability of the ground is a constant worry, earthquakes are yet another factor to be considered when planning and developing a road network.

The bedrock of Norway varies in rock type from region to region. It contains many natural resources, such as ores, minerals, and oil-bearing layers of shale. It also contains hazards such as quick clay and groundwater courses, which make planning and building road networks difficult. Quick clay[5] is a special type of clay, primarily found in Norway, Sweden, and Canada, which collapses and liquefies when overloaded. Quick clay can be a real issue for road engineers in Norway, as when subjected to sustained loading from anthropogenic structures, the clay mass can rapidly transform into a floating liquid, causing sudden ground motions which in the past have wiped out houses, infrastructure and caused many deaths.

Figure 2-1: Quick clay landslide at Lyngseidet, Sept 3, 2010 (220.000 m3). Photo: Andrea Taurisano, NVE

4 Why are there mountains in Norway? NGU article

5 https://www.ngu.no/en/topic/quick-clay-and-quick-clay-landslides

The Rissa landslide in 1978 [6]is particularly well known because by chance it was filmed. This involved an area of 330,000 m^2 and resulted in one death. Another large slide occurred in 2010 at Lyngseidet (see Figure 2-1).

Sensitive clays including quick clays are potentially present in areas located below the Marine Limit (ML), defined as the highest former sea level following the Holocene deglaciation. The ML varies considerably in Norway. The highest ML is present in the Oslo region (ca 220 m above sea level) and in central Norway (up to ca 200 m above sea level). Using the modelled ML available from NGU (http://geo.ngu.no/kart/losmasse_mobil/), the calculated area under the ML in Norway has a limited extent of ca 12.000 km^2. This corresponds to 3.7 % of the area of mainland Norway. Although these areas are geographically limited, they constitute the most densely populated parts of Norway. A substantial proportion of major and complex construction projects are taking place in these areas. However, it is also important to keep in mind that even a limited and local occurrence of potentially unstable clay may cause considerable difficulties and extra cost to infrastructure projects.

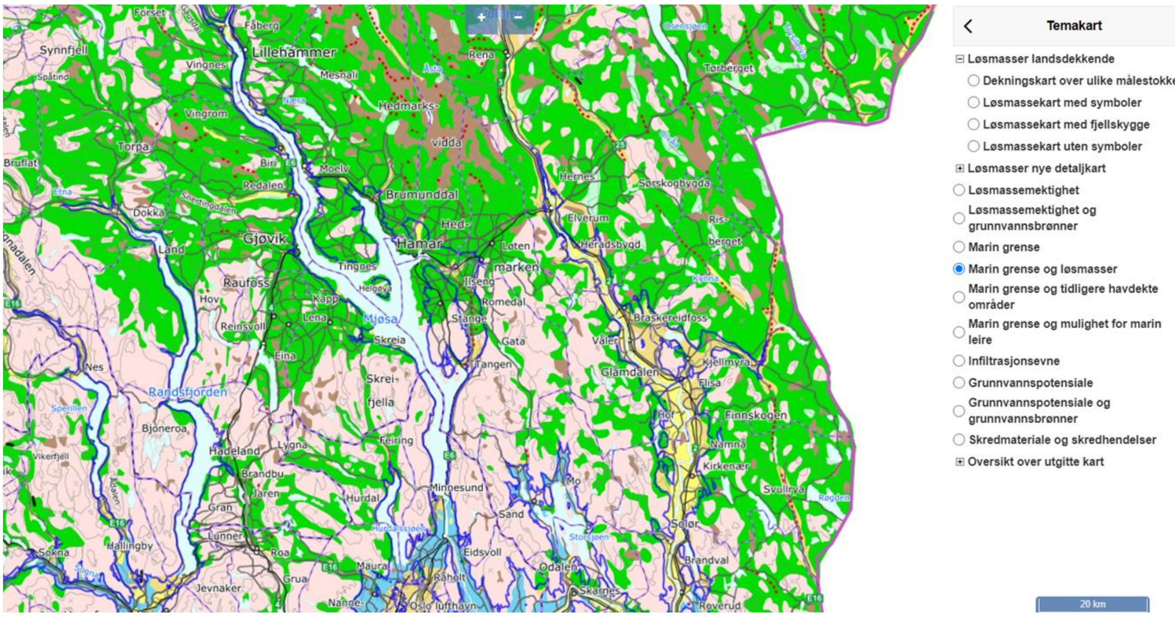

Figure 2-2: Part of Norway showing the Marine Limit (ML) extending up many valleys.

Figure 2-2 shows that the Marine Limit ML (blue border colour in the map in the Figure) and areas below the ML can stretch far into the country along large valleys where infrastructure is being built.

Groundwater is another issue which requires consideration and protection by the road authorities. Human activities and infrastructure development can adversely affect groundwater, which is

[6] https://en.wikipedia.org/wiki/Rissa,_Norway

protected by various laws to ensure sustainability[7]. Road construction activities, such as tunnelling and pile driving, can affect the water table. Numerous instances have been recorded of road construction works, especially piles, disturbing the artesian pressure of the groundwater, which in turn leads to rapid ground deformation and powerful flooding events.

Tunnels can both adversely affect groundwater courses and also be affected by groundwater themselves. Groundwater, naturally occurring in sediments and bedrock, may cause leakage as well as instability during tunnel construction. Tunnel leakage can lead to construction challenges and be a major headache for tunnel engineers. “Grouting” is a preventive measure that involves injecting these cracks as well as the outside of the tunnel walls with a special type of filling cement. Grouting helps stop leaks and also aids the structural integrity of the tunnel and the ground above. Water leakage at tunnel depth commonly propagate upwards and affect the groundwater level, causing compaction of sediments, alteration in pore pressure or degenerates organic structures closer to the surface[7]. As with any activity that entails changing the composition of the underlying earth, ground subsidence is something that must constantly be monitored by the engineers during grouting operations. Water-related processes are slow, where the visual damage at the surface may appear years after the construction. Monitoring of ground motion at mm precision, will enhance the ability for counteraction and decrease damage.

A further problem facing the road constructors and planners is the presence of moraines where ancient glaciers have deposited softer material. The city of Oslo is situated at the northern end of the Oslo fjord, in a sedimentary basin formed during the last glaciation period. These glacial structures have since then been covered with marine sediments, mostly clays. In the area around the main train station, the sediment layer is 94m in depth, meaning that the bedrock on which the construction will be built requires at least 94m piling[8].

Figure 2-3: Dronning Eufemias gate, which is more like a bridge than a road.

[7] Groundwater; [NGU information note.]
[8] TU1206 COST Sub-Urban WG1 Report.

Since 2000 the Bjørvika area in Oslo city has been refurbished from a harbour area to a new and modern living and working quarter with high-profile buildings such as the Opera house, the Deichmans National library and the new Munch Museum. The geotechnical conditions are quite difficult. As an example, the road, Dronning Eufemias gate, which is running parallel to the seafront, looks like a road at the surface, but it is actually a bridge built upon 1100 pillars of steel and concrete.

The new constructions are all anchored to the bedrock at depth by piles and metal sheets, which makes them stable and secure. However, the construction at the waterfront has disturbed the groundwater level and altered the pore pressure in the marine clay, which has triggered or increased subsidence in the older city area. Increased ground motion has caused damage to the older buildings, which restoration is estimated to €6 billion[9].

2.3 An integrated transport network

It is not just roads that face these difficult geological conditions. Railways and other infrastructure are also impacted (as we see above for the Oslo main train station), and in many cases, the problems become linked.The Norwegian rail network comprises just over 4,000km of track. It has 696 tunnels and 2760 bridges[10]. Roads and railways often run alongside each other, and the planners of Bane NOR (which builds and maintains the tracks) work closely with those of the NPRA. In many ways, the railway is even more affected by the state of the ground than the roads.

For some projects, the links are very close[11], as in the case for the construction of the new InterCity Østfold Rail including a new railway station in Fredrikstad. The new station is planned as a commute centre for the region, which requires new road infrastructure to facilitate both pedestrians and traffic. The ground conditions are poor and challenging, and the project has run into considerable difficulties.

[9] Pathways & Pitfalls to better Sub-Urban planning (2018) https://issuu.com/ngu_/docs/suburban_magazin_pages

[10] Wikipedia: Rail Transport in Norway

[11] BANE NOR Intercity: https://www.banenor.no/Prosjekter/prosjekter/intercity/hvorfor-intercity/

Figure 2-4: Norway rail network

Insufficient understanding of the poor ground conditions present at the construction of the new railway infrastructure near the city of Fredrikstad has added billions of Norwegian kroner to construction costs and ground the project to a halt. Bane NOR, the government agency responsible for building, maintaining, and operating the Norwegian rail network, has reported that the proposed development of the multiple sections of the network from Fredrikstad to Sarpsborg will require NOK 29 billion more to proceed compared to the original estimate of NOK 8 billion. The main issue impeding the development is the unexpected extreme depths that must be reached to obtain stable bedrock for foundations. The ground stability in Østfold county, south of Oslo, where Fredrikstad is located, has long been known to be poor. However, the extent to which construction works must dig to obtain a solid foundation, as well as the instability of the clay in the region, was not truly appreciated. In some places, the bedrock is over 130m below the ground surface. Statens vegvesen, who have multiple interface points with the project where new roads are to be constructed alongside the railway, also found ground stability to be a real issue in this area.

Grønli is the area in Fredrikstad where the new railroad and station with connecting infrastructure is planned. The area has been in development since the end of 1880. Although the routes are old, the infrastructure has evolved, including bridges and roundabouts. A pedestrian bridge built in 1987 shows substantial damage due to ground motion and subsidence.

Figure 2-5: Pedestrian bridge built in 1987 crossing Rolvsøy road at Grønli in Fredrikstad. Subsidence of the ground causes damage to the bridge on both sides. (Photo. Guri Venvik, NGU)

The cause of subsidence in the Grønli area is complex and groundwater plays an important role[12]. During construction of the bridges at R 110 crossing Rolvsøyveien, several drill holes were made for inspection. The drill holes were not properly blocked when terminated and groundwater leaked to the surface. The groundwater was from an artesian aquifer, with higher pressure than atmospheric pressure and will continue to flow if not prohibited.

Punctuation of the artesian aquifer and the increasing load of additional buildings and infrastructure lead to a reduction in pore pressure and compaction of sediments which are processes that could cause ground motion and subsidence. These slow processes are complex and interlinked. The use of InSAR data will give an advantage in understanding the complexity and a tool for prognosis of risk areas. Ground stability has been measured at several locations in Grønli from the beginning of 1970 until today. InSAR confirms the subsidence trend of approximately 4 mm/year, with no indication of termination.

[12] NGU Internal Report: Venvik et al., 2019. lnterCity-prosjektet, Østfoldbanen Fredrikstad - Sarpsborg. Faglig radgivning rundt geologiske forhold i Fredrikstad. ICP-16-A-00017, rev. 01A. NGU report 2019.028

2.4 Where Ground Motion becomes Important

2.4.1 Challenges faced

The transport infrastructure plays an enormously important role in a nation's development. As a country's economy develops, the transport infrastructure must adapt to changing local and national priorities. For instance as new commercial centres, industrial parks or residential zones are created, new traffic flows may be anticipated necessitating both new and improved roads and railways. This constant adaptation is essential to maintain an effective traffic flow contributing to national progress.

Organisations such as NPRA in Norway, need to respond to the demand for new roads by local authorities eager to see their town or region develop and grow. At the same time, these demands need to be balanced with financial budgets and environmental pressures. Processes to manage these demands and conflicts have evolved in each country and it is fair to say that the governance of the process diverges greatly between countries.

The ground motion maps can contribute to meeting these challenges in many ways which will be discussed during this report. We can identify, in a very general way, 4 phases of activity linked to the development and operation of the transport infrastructure – our case focuses as already stated on roads. Not all administrations will follow the same process but we can identify, in general, 4 phases of works:

- Planning phase when the project is first addressed, the budget must be established and the broad conditions for the development must be understood. Planning with respect to road construction takes into account present and future uses of the transportation system to assure maximum service with a minimum of financial and environmental cost. The route the road will take will be established as having a strong impact on the cost. The main objective of this initial phase of road development is to establish specific goals and prescriptions for road network development along with the more general location needs.
- Design phase when the nature of the road project will be established as well as the design to the point where the specifications are clear. This will include more detailed geological surveys and engineering analyses leading up to the point where the project can be tendered.
- Construction phase where the engineering works take place.
- Operations & Maintenance phase where the road is opened to traffic and ad-hoc work is required to resurface or repair damage. The use and safety of the road will be monitored.

In order to understand the use and impact of the ground motion map on the management activities, we have identified projects in Norway where ground movement is or has been a problem and which enable us to examine what benefits the ground motion map service can deliver.

2.4.2 Building a Bridge at Sifjord

Sifjord is a remote fjord, situated on the west coast of Norway's second-largest island, Senja, in the far north of the country. Sifjord contains a small fishing community of the same name, which over the years, has unfortunately been struck by tragedy. On a particularly treacherous stretch of road, at the source of the fjord, fatal rockfalls have caused death in the past[13]. Locals have become understandably wary of driving on this particular stretch of road, not knowing when the next tragedy could strike. To avoid any more tragedies in this quiet, idyllic community, a solution had to be found.

The road authorities decided a bridge that stretches from one side of the fjord to the other, avoiding the need to drive around the dangerous, narrow part of the fjord, would be the optimum solution. To build the foundations of the bridge, a huge amount of filling rubble was required to be dumped into the fjord and built up until it breached the waterline. This filling was, in turn, used as a stable foundation on which the road and surrounding bridge infrastructure were built. However, in order to begin the road infrastructure work, settlement of the filling rubble first took place. This settlement usually takes several years, with the highest settlement velocities the first year. Measuring the settlement can be laborious and/or expensive using traditional field methods. In this instance, the company in charge of measuring the settlement, Multiconsult, is based in Tromsø, a 3-hour drive away from Sifjord. Due to Sifjord's remote location, the monitoring of the settlement of the filling rubble using traditional in-situ instruments would have taken up much time for engineers at Multiconsult. This is where the use of InSAR technology came into play. By installing corner reflectors at strategic locations on top of the filling rubble, engineers at Multiconsult could monitor the settlement remotely, continuously and accurately. This avoids losses of time and money when compared with measuring settlement using in-situ instruments. Tiny changes in elevation of the filling rubble were observed using the InSAR technology, with updates on the progress of the settlement being obtained every six days thanks to Sentinel-1 data processed by Norce. In remote areas, or areas susceptible to closed roads due to bad weather or risk of avalanches, InSAR can give continuous measurements. This can give a better foundation for decisions during building projects.

[13] NRK, News article, https://www.nrk.no/tromsogfinnmark/_-jeg-tenker-pa-henne-hver-gang-jeg-kjorer-forbi-1.12362887

Figure 2-6: The foundations of the bridge at Sifjord

2.4.3 The Frodeåsen tunnel in Tønsberg

The city of Tønsberg is located about 100km south-west of Oslo. Since the opening of the Frodeåsen dual road tunnel in 2008, which connects the city to a major highway, numerous issues have cropped up at the eastern mouth of the tunnel. Engineers were perplexed when they found that cracks in the concrete structure were beginning to appear, exposing previously buried cables and creating height discrepancies in parts of the road and surrounding infrastructure (Figure 2-7 and the front cover). Surveys were initially undertaken locally, aroundá the mouth of the tunnel, and subsidence in the immediate vicinity was noted. How far and to what extent this ground subsidence reached was still, unfortunately, unknown.

A report published in 2017[14] noted that;

> *Repair work has been going on for several years. This entails large costs, currently NOK15 million (€1.5m). The improvement in 2017 has also resulted in a burden for road users since the road over the tunnel has been closed.*

[14] Report on Frodeåsen tunnel (in Norwegian), Jan Krømcke, WSP Norge AS and Dag Atle Tangen, ViaNova AS, September 2017.

Figure 2-7: An example of some of the structural cracking of the Frodeåsen tunnel infrastructure in Tønsberg

The report went on to conclude that:

> *So far, no obvious and unambiguous cause has been found for the subsidence in the tunnel. SVV has, with both experts and hired experts, sought to find the cause, without being able to conclude unambiguously.*

Various reasons were put forward, but none were conclusive, and none were the reality.

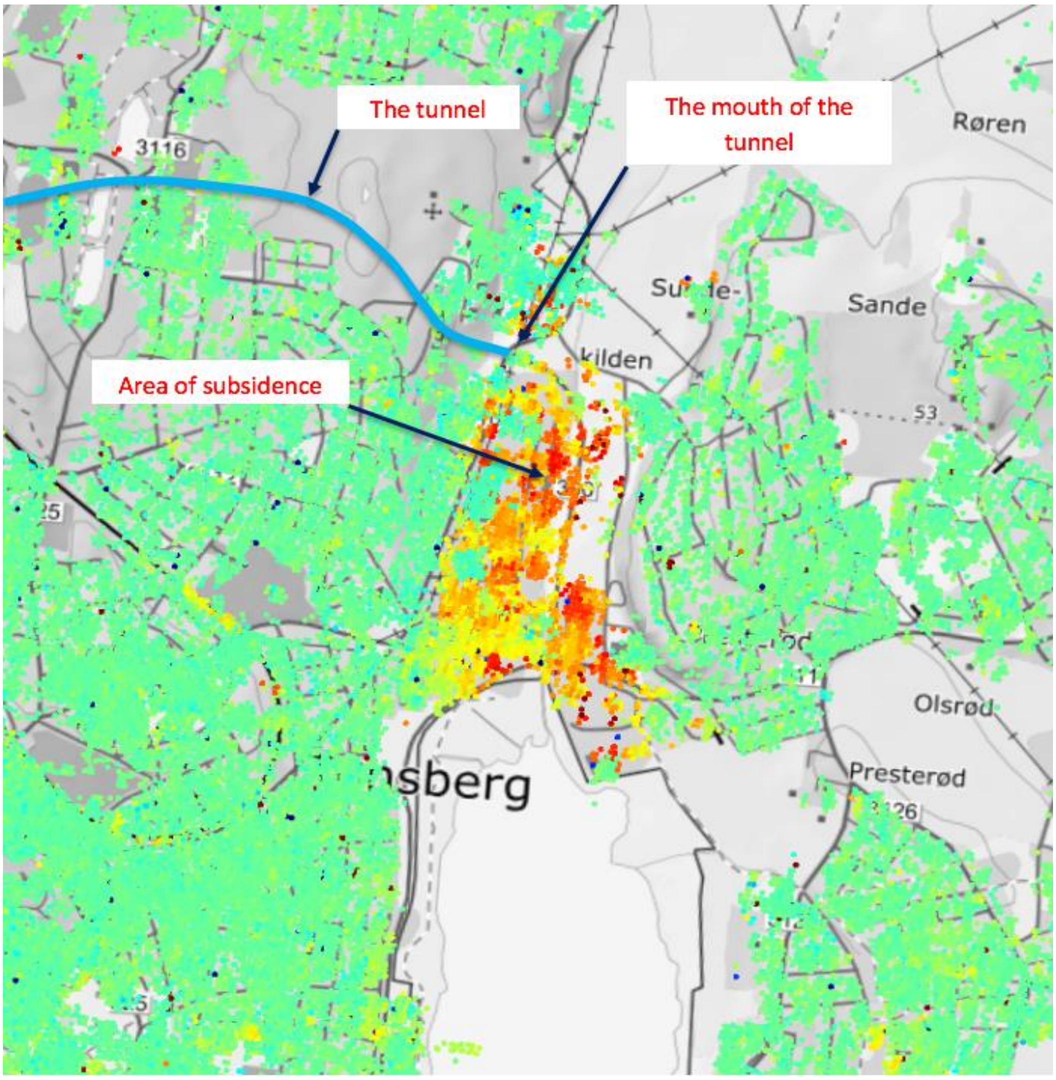

Figure 2-8: The Tønsberg tunnel with ground subsidence shown in yellow/red – InSAR Norway

It was only when InSAR technology was made available through the Norwegian ground motion service, InSAR Norway, that the engineers began to see the full picture. The InSAR Norway map immediately indicated that the entire area to the south-east of the tunnel, beginning near the mouth of the tunnel, was experiencing substantial ground subsidence. The tunnel entrance lies at the edge of the area that is moving and hence is undergoing stresses. Thanks to the historical data available, the engineers could also see that this subsidence had been happening for a number of years.

Had the engineers understood the poor ground conditions at the eastern end of the tunnel during the planning phase of the project, they could have implemented mitigation measures, or even design changes to ensure that the kind of damage currently being experienced would be avoided. Currently, the tunnel is still operational but requires repair works regularly around its eastern entrance/exit. These works include resurfacing of the road and the construction of small ramps to maintain the operability of a cycle path that intersects some of the affected infrastructures.

Undertaking these works requires the closure of one of the two tunnels, which affects the flow of traffic and costs money each time. Tønsberg is shown on the InSAR Norway map (Figure 2-8), with the Frodeåsen tunnel highlighted in blue and the yellow/red region indicating the substantial area of subsiding ground, just at the mouth of the tunnel.

2.4.4 Bjørvika

In Oslo, Bjørvika is a major re-development area located between the railway station and the seafront. The highway running along the harbour front is now going through a tunnel beneath the fjord, and the harbour has moved a couple of kilometres south, a major action that has freed large surfaces for redevelopment in the central parts of the city. While most modern buildings are founded on piles that reach down to bedrock, many historic buildings, including the station, are built upon wooden foundations. Even if new buildings are stable, settlements in the surrounding areas may affect infrastructure connections, such as water pipes and electric cables[15].

Figure 2-9: Ground motion map of the Bjørvika neighbourhood of Oslo 2009 to 2013[16], based upon Radarsat-2 data.

Recently, it has been claimed that the Barcode development in the area, could have accelerated subsidence by altering the groundwater table and reducing pore pressure in the sediments. A lowered groundwater table could also lead to degradation of wooden foundations that are now exposed to an oxidizing environment. Figure 2-9 shows the InSAR Norway map of the central parts

[15] Oslo Underground 2013-2017

[16] Oslo, TU1206 COST Sub-Urban WG1 Report

of Oslo, where orange and red points are those where ground motion has taken place – in this case, between 2009 and 2013. The processes causing the subsidence in the Bjørvika area are complex, interlinked and not fully comprehended. The use of InSAR data is an efficient tool to identify areas of risk of subsidence and thereby damage when development is planned.

2.5 Social and Environmental Considerations

In environmental terms, transport is often criticized for its contribution to global CO2 and particle emissions. However, this relates to the total emissions emanating from cars and lorries and, as efficiencies rise, emissions fall, and total traffic stabilizes, new roads can reduce travel time and hence corresponding environmental impacts.

Whilst knowledge of the ground stability is a key input into estimating the project cost, it has no impact on the environmental impact of the built road, nor for the construction period. Hence, there are not considered to be any significant environmental benefits of using ground motion maps. The stability becomes one further factor to take into account when deciding routes to follow and may even help reduce impacts by reducing the risk and/or occurrence of road closures and subsequent congestion. But the direct environmental impact is considered to be low or negligible.

The construction of underground structures may also have an impact on aquifers and water flows. Building a tunnel may divert water from one area to another with potential consequences for farmers and local citizens. Piling, where a column penetrates various sub-surface strata before reaching bedrock, may cross layers of clay and impermeable rocks, so allowing water to rise to the surface. This can distort the clay layers as well as cause subsidence as pressure is released. This is one of the most common causes of subsidence arising from infrastructure construction.

Alkthough we have not come across any specific examples, works are sometimes left uncompleted due to budgetary or planning difficulties. It is not impossible that becoming aware of an instability, which could significantly lead to an increase of cost and a project abandonment, could be avoided by earlier knowledge of ground motion.

One identifiable benefit, albeit small and indirect, is that the use of ground motion maps to detect slope instability and potential rockslides, reduces the need to fly helicopters around the country.

However, whilst InSAR can help to detect surface distortions, it has very little impact from an environmental perspective. The climate and environmental benefits are considered to be very small.

2.6 Data for Informed Decision Making

2.6.1 What decisions?

What types of information will be useful to the road planners and builders to improve the decisions they are making, and how can satellites help? What decisions can be affected and improved? This varies according to the phases of the projects.

Planning phase: Here the decisions being taken are preparing the business case for the proposed road development. A key decision at this time is to select the route and establish legal approvals. Knowing the stability of the proposed route and avoiding parts which have been historically vulnerable can avoid future issues – as in the projects in Fedrikstad and Tonsberg. The use of InSAR provides a unique means to understand the scale and velocity of any movement. It can also identify the degree of risk due to rockslides. The ground motion map will provide easy access to this information which would not be available by any other means.

Design phase: Decisions taken during this phase relate to the type of road construction method to be used. In the case of Tonsberg, the large extent of the movement was not visible to engineers until the ground motion map made it available. Seeing the extent of the movement would have led to changes to the design of the tunnel – even if it would not have changed the route. Either way, the design decisions would be taken knowing where the ground is moving and, most importantly, how fast it is moving in the different parts of the proposed route.

Construction phase: activities during the construction process can themselves trigger ground movement. Decisions taken during this phase relate to detailed engineering and construction tasks. These include the safety of the project and the security of the design. Monitoring for unexpected ground movements can indicate unforeseen problems (ie consequences of drilling through impermeable layers) or foreseen ones (settlement of ballast or deposited materials).

Operations phase: concerns the longer term stability of the road. As in Tonsberg, unexpected consequences can be detected and new conclusions may be drawn. Knowledge of ground motion can help decisions related to timing of maintenance works.

2.6.2 What Data?

Three types of data can be relevant. Firstly, information on any movement of the ground which may have arisen before any road construction, during the construction or after the works are finished. The spatial resolution of the measurement needs to be consistent with the type of area, i.e. urbanised or countryside. The time separation between measurements needs to be consistent with the type of operation, i.e. close enough in time to detect problems during construction works but may be less frequent as part of the planning phase. The rate of movement is important as an indicator in some situations.

Secondly, information on potential landslides. Many areas of mountainsides around Norway are unstable and pose a threat to roads, railways, and other infrastructure in the case of collapse. NGU introduced the InSAR Norway service as a means to help detect, understand, and monitor these unstable areas.

Thirdly, avalanches also pose a threat to road users and, whilst the use of InSAR in snow-covered areas is not possible, a service has recently been introduced whereby areas at risk are monitored with SAR-based change detection.

2.6.3 Limitations of Conventional Methords

In terms of measuring ground motion, conventional methods are very limited. Alternative methods do exist to measure the movement of the ground surface, but these are either less accurate, more expensive or limited in area covered. Only InSAR can offer all three of these attributes:

- Traditional surveys cover a limited area and are labour intensive. They can be made with high precision and close spatial sampling, but require a lot of time to be able to measure the movement regularly.
- Overflights using Lidar are expensive to undertake and hence not really suitable for regular measurements even though the accuracy and the spatial resolution are excellent.
- Augmented GPS measurement requires investment in equipment and is limited in accuracy.

In reality, due to the limitations of more conventional methods, ground motion is rarely investigated by road designers. Knowledge of the geology and where problems are likely to occur are mainly used as a guide. InSAR has the potential to be a key tool to be used by road designers and engineers.

3 The Use of Sentinel Data

3.1 How can Satellites help with Roads Management?

In this chapter, we look in more detail at how satellite data can help to improve the development and management of the road system in Norway. We describe the sources of the satellite data which provide the information services being used by the NPRA and others. Our main focus is on the use of the product "InSAR Norway," which is an annual, country-wide, ground motion map. However, roads are also susceptible to landslides and avalanches, so we shall also introduce a short description of both the landslide and avalanche detection services, also being used by various actors in the value chains.

Both of these services are based on the use of Sentinel data coming from the European Copernicus programme, so we shall start with a simple overview of the programme to place the services into context.

3.2 Copernicus and the Sentinels

Copernicus is an EU flagship programme[17]. Copernicus started out as GMES (Global Monitoring for Environment and Security) with the goal of meeting European geo-information needs. At its heart is the most complete, operational satellite system in the world; owned by the EU and operated by ESA and Eumetsat and currently comprising six types of satellites (see Figure 3-1). The InSAR Norway service is using data coming from the Sentinel-1 series of satellites.

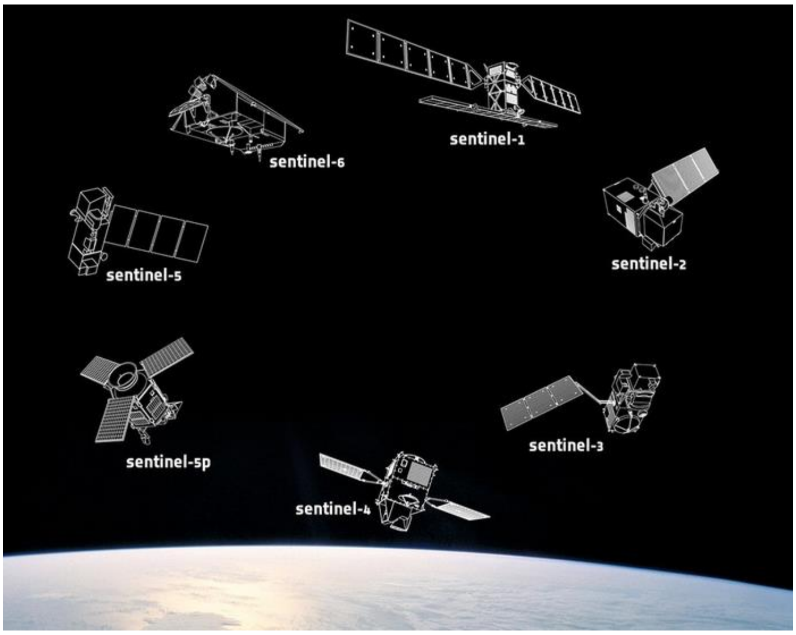

Figure 3-1: Current Sentinel satellites

[17] https://www.copernicus.eu/en

Copernicus is the flagship programme of the EU to provide EO derived information services to EU policymakers. In addition to the space segment, there are also six downstream Copernicus services, as shown in Figure 3-2.

Figure 3-2: Copernicus Services

Our case is defined by Sentinel-1[18] , which carries a Synthetic Aperture Radar (SAR) operating in C-band. During the last decades, radar satellite technologies have proven their usefulness to monitor the Earth thanks to the all-weather, day-night capability and the many applications that can exploit their data. More and more application opportunities have emerged, thanks to the improved capabilities of the new space radar sensors in terms of both resolution and revisit time.

In particular, a technique, known as InSAR (Interferometric Synthetic Aperture Radar), uses several observations of the ground at intervals of days, weeks, months, and even years, and, using Multi-Temporal Interferometry (MTI) algorithms, can detect vertical movements of the Earth's surface of a few millimetres that have occurred between the observations. This technique has proven extremely attractive for different areas of risk management, such as monitoring of subsidence, volcanoes, tectonic movements, urban areas, and infrastructure and slope instabilities. In particular, the technique allows detecting and monitoring millimetric displacements occurring on selected point targets exhibiting coherent radar backscattering properties - hence the interest for NGU and NPRA for highways management. For those interested, a more detailed explanation of the InSAR technique is included in Annex 4.

Sentinel-1 is the latest SAR mission launched by ESA with the first - Sentinel 1A – going into orbit in 2014 followed by Sentinel-1B in 2016. The two-satellites Sentinel-1A and 1B provide high-reliability

[18] https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-1

The satellite data:

Sentinel-1 is the Copernicus radar mission, providing an all-weather, day-and-night supply of imagery of Earth's surface. The mission consists of two satellites embarking C-band synthetic aperture radars (SARs) in continuity of the ESA's ERS-2 and Envisat missions. the mission images the entire Earth every six days for the benefit of manifold applications such as, for example, monitoring of Arctic sea ice extent, surveillance of the marine environment, monitoring land-surface for motion risks, mapping for forest, water and soil management.

Copernicus Sentinels data are available under an open and free data policy.

Sentinel-2 data can be accessed at https://scihub.copernicus.eu

More info: https://sentinels.copernicus.eu

Figure 3-3: Summary of Sentinel 1

data with a short revisit time, global coverage and rapid data dissemination to support operational applications.

The Norway ground motion map will develop a historical perspective of the whole country so that in a few years time, planners and engineers will be able to see if a particular area of ground is susceptible to movement. Today, data is also available through archives from earlier missions: ERS-1/2 and ENVISAT (ENV), which allows ground instability analysis to be performed back in time almost all over the Earth. Coverage is not complete and hence there is an element of luck if a particular area was imaged sufficiently or at all to enable InSAR maps to be generated. Where the data is available, it is the only tool able to develop a historical map of ground motion going back to the 1990's when ERS-1 was operational. Furthermore, several other missions also now offer SAR data, which can be used in complement to that from the Sentinel mission. These include higher spatial resolution data, i.e. measuring points which are more closely located on the ground, which is necessary for some applications.

The analysis of ground and structure deformations to support the planning, design, construction, and operational phases of developing and maintaining highways, can benefit from increased exploitation of affordable remote sensing systems. Synthetic Aperture Radars (SAR), such as that on Sentinel-1, are playing a crucial and growing role. Sentinel-1 offers regular global-scale coverage, free imagery, and improved revisit time (less than six days) and can now guarantee wider and more efficient application of InSAR for global infrastructure monitoring, which is now being applied to the case of highways management in Norway and other countries.

3.3 How can satellites measure ground motion?

A SAR system emits microwave pulses (with a wavelength ranging from few centimetres to few tens of centimetres) and records the echoes from each pulse. The time taken for the echo to arrive provides the distance between the satellite and the measurement point on the ground. The energy that is reflected or scattered back from the ground provides important information on the surface. Since microwave radiation penetrates the atmosphere with negligible absorption, SAR is capable of operating during all weather conditions and at night. These properties for all-weather and night-day acquisitions make this technology very appealing for Earth surface monitoring purposes.

SAR data are intensively used for the measurement of ground and structure deformations and the key technique used for the data processing is typically mentioned in literature as Multi-Temporal Interferometry (MTI)[19]. MTI has shown, in the last two decades, strengths and capacities in terms of wide area coverage (several tens of thousands of square kilometres) over long periods (several years). With MTI, successive SAR images are compared so that the distance between known points are compared. When these have changed, the radar can detect this.

The basis of MTI (InSAR) is that the radar can measure to high precision when a point on the ground has moved closer or further away from the radar. As the satellite looks towards the Earth on an angle (referred to as Line of Sight, or LOS), it can detect both vertical and horizontal displacements, but not differentiate between them with a single set of data. As the radar signal hits the ground, the intensity of the energy reflected is determined by the nature of the ground surface. If this is strong and stable from one image to another (which may be taken days, months, or even years apart, then changes in (the phase of) the signal enable the LOS distance to be measured.

The nature of the ground surface is highly important. A pixel can be used for ground motion estimation if the contributing scatterers within a single pixel don't change their relative position over long periods with more than a fraction of the radar wavelength (5.6 cm in the case of Copernicus Sentinel-1 constellation), which is called *coherent scattering*. If it is covered in vegetation (as in many rural areas), then the signal is weak and changes (caused by growth, wind etc) cause the signal to become decorrelated[20] and not useful for measurements of ground movement. This is equally true over large flat surfaces where the reflectance is poor ie water bodies.

On the other hand, over man-made and rock surfaces, a strong reflection can come from single points. These are highly effective to measure ground motion. In some cases, a very strong and dominant reflector (known as a corner reflector) may even be placed specifically to help measurements (see the later description of measurement of ballast settlement). Otherwise, road signs, roadside barriers, and other metal objects will provide good measurement conditions – which is often the case along roads.

As an illustration, see Figure 3-4 and Figure 3-5 showing extracts from the InSAR Norway service[21]. The two figures show clearly how in vegetated areas, there are few points of reflection as evidenced here by the lack of coloured dots. In the right part of Figure 3-4, we can see the area around Tønsberg which has been moving and troubling the Frodeåsen tunnel. On the left-hand side of Figure 3-4, two roads stand out with some motion evident by the coloured dots. But all sit along

[19] J. Wasowski, F. Bovenga, "Chapter 11 - Remote Sensing of Landslide Motion with Emphasis on Satellite Multitemporal Interferometry Applications: An Overview", Science Direct, Landslide Hazards, Risks and Disasters, 2015, Pages 345-403, https://doi.org/10.1016/B978-0-12-396452-6.00011-2

[21] Norwegian ground movement mapping service - https://insar.ngu.no/

the road, and to either side, there are no reflectors. The fields are bare as it were. What we are seeing are road signs and barriers beside the roads that are giving good reflections.

In Figure 3-5, we can see a small zone that is subsiding evidenced by the coloured dots in the centre of the picture. All around are bare areas or green dots where there are man-made objects – mainly houses. These reflectors are on objects which have not moved from one year to the next. So the green dots are reflecting points in the image that have not moved, whilst the coloured dots are showing some movement between the radar images.

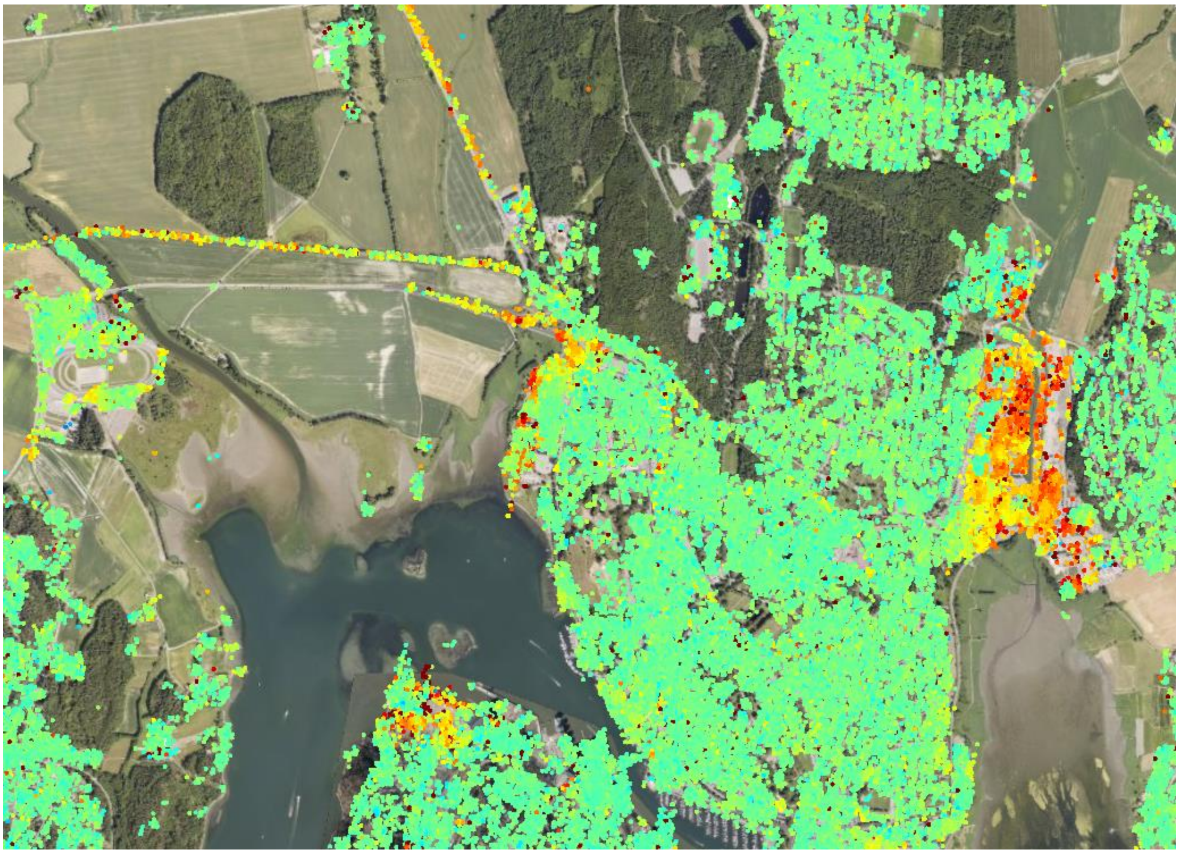

Figure 3-4:InSAR Norway view of Tonsberg and surroundings[22].

[22] https://tinyurl.com/rqgkdvp

Figure 3-5: The village of Nøtterøy (https://tinyurl.com/rqgkdvp).

The spatial resolution and the frequency of observations are both important characteristics in determining where the InSAR ground mapping may be used for effective highways management.

- The spatial resolution determines how far apart points on the ground may be detected. The nature of the ground is very important so that built-up areas, with many reflectors in close proximity, require much higher resolution in order to identify which point has moved. Higher resolution images help solve this problem but are generally commercial compared to the Sentinel-1 data, which is free. InSAR Norway currently provides data for over 3.8 billion measurement points over Norway; an average density of 11 000 measurement points/km^2.
- The frequency of the observations depends on how often the satellite passes overhead and if images are being collected. Very high spatial resolution satellites generally are imaging smaller “swaths,” i.e. smaller areas on the ground, and hence tend to observe the target less frequently. Sentinel-1 has a larger swath width and can provide InSAR compatible images every six days, with 4-8 times overlapping passes for each location in Norway. There is a direct trade-off between spatial and temporal resolution.

The availability of images from many satellites increases the ability to measure movements with very high spatial resolution or with a shorter delay between each measurement. Note that only images taken with the same satellite may be used in MTI processing to generate ground motion maps.

Some missions also offer very high spatial resolution (e.g. 1 m or less with COSMO-SkyMed and TerraSAR-X). These allow points on the ground (or on building or other infrastructure) that lie close to each other to be distinguished. In this case, the lower resolution but free Sentinel data may be used as a trigger to acquire higher resolution commercial data. However, the temporal sampling of the higher resolution data may be longer than for Sentinel with a wider swath coverage leading to a trade-off. We have seen this in many other cases.

The use of Sentinel-1 compared to the other SAR constellations gives the following advantages:

- The wide swath leads to a short revisit period meaning that it is possible to detect signals from targets that are changing more rapidly and detect ground motion adjacent to roads.
- The spatial resolution is adequate to allow the detection of ground motion and is sensitive enough to indicate where precise problems may be occurring, thus providing a trigger to look more closely at what is happening. This may be performed with higher spatial resolution InSAR or other direct measurements such as inspection or surveying.
- The free SAR data means that routine InSAR processing can be carried out in a cost-efficient way for infrastructure monitoring.

Generally, current capabilities do not allow near-real time monitoring several times per day. Ground motion can only be detected over periods of days, weeks or months. This is sufficient for many applications associated with highways management, where the rate of motion is generally slow. Hence, as seen in the case of InSAR Norway, there are several ways in which the technique can be used:

- Monitoring of unstable ground leading to remedial measures to prevent or mitigate the impact on road infrastructure
- Monitoring of tunnels and bridges to detect problems before they become widely visible
- In certain conditions, to detect where stresses are occurring in anthropogenic structures (bridges) to identify structural problems.

The use of InSAR to monitor bridges has been the subject of some research projects. In March 2001, a bridge collapsed in Northern Portugal, causing 59 deaths. Analysis of 52 ERS-1 SAR scenes acquired in the years prior to the collapse showed that significant motion of the ground was occurring[23]. The research showed that many measurement points are possible for fixed, man-made structures such as bridges using moderate resolution satellite radar imagery, and that Sentinel-1 will be able to meet many of these needs in the future.

A second study[24] looked at three bridges in Bratislava, Ostrova, and Hong Kong. It concludes that while for new constructions, sensitometers can be built into a monitoring system, effective satellite-

[23] Multi-temporal SAR interferometry reveals acceleration of bridge sinking before collapse. J. J.Sousa and L. Bastos. Natural Hazards and Earth Systems Science Journal 2013.

[24] Potential of satellite InSAR techniques for monitoring of bridge deformations. Milan Lazecky, Danielle Perissin, J. Sousa, Nuno Real. Conf Proc. Joint Urban Remote Sensing Event 2015.

based InSAR monitoring can take place, on a temporal and spatial basis and that this is most appropriate for existing bridges.

In a third example, a study[25] has examined whether the dramatic and tragic accident due to the collapse of the Morandi bridge in Genoa, Italy could have been avoided. The study led by JPL in the US, concluded that it may have been possible to detect early signs of movement but that InSAR would not have provided an alert to the collapse.

Technical issues surrounding the detection of motion require man-made reflectors to be visible in the scene being imaged. In most cases, the presence of road signs, panels, and barriers around vulnerable areas will enable the motion to be detected quite accurately.

3.4 The Norwegian Ground Motion Service – InSAR Norway

The Norwegian Ground Motion Service is the culmination of many years of cooperation between the Norwegian Space Agency (NSA), the Geological Survey of Norway (NGU), and NORCE Research (formerly Norut). Already in 2004, NSA and NGU agreed upon the importance of developing InSAR technology for use in the Norwegian public sector. The Earth Observation group at NORCE led the development. Early developments used data from the ERS-1 and ERS-2 satellites. Later, in 2009, systematic acquisitions of Radarsat-2 data over large parts of Norway were started.

[25] Pre-Collapse Space Geodetic Observations of Critical Infrastructure: The Morandi Bridge, Genoa, Italy Pietro Milillo, Giorgia Giardina, Daniele Perissin, Giovanni Milillo, Alessandro Coletta and Carlo Terranova.

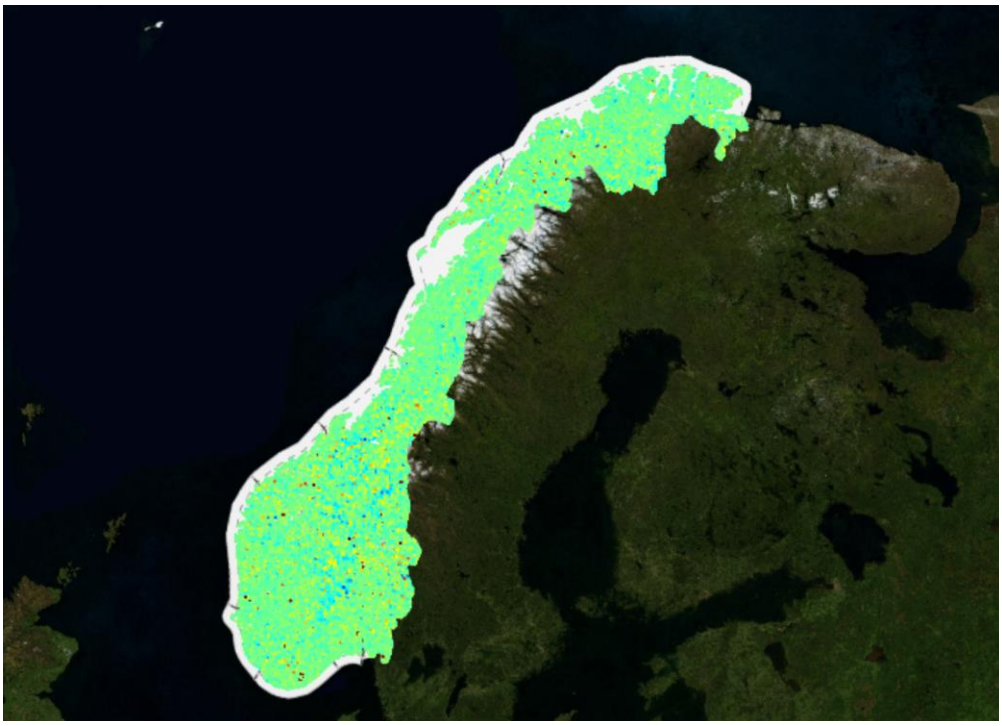

Figure 3-6: The ground motion map (insar.ngu.no) covers all Norway and is at present updated once per year.

The initial idea for the InSAR Norway service was developed in 2013/2014, through a working group with members from NSA, NGU, NVE and the transportation authorities. Their mandate was to define a strategy for future optimal use of InSAR and the upcoming Sentinel-1 data within the Norwegian public sector. A white paper was released in May 2014, recommending a national ground motion service[26] to be established, operated by NGU.

One driver behind the service was providing InSAR services that could be of use to the road, rail, and other public authorities for mapping and monitoring of infrastructure subsidence. An equally important driver for the service was the serious and deadly issue of landslides. NGU, NVE and the Norwegian Space Agency all felt InSAR technology could be better exploited to help foresee potentially disastrous landslides and put measures in place to alleviate the harmful results.

After Norway began contributing to the EU Copernicus programme, the national Norwegian Copernicus programme was started in 2015 with funding from the Norwegian Space Agency. The project InSAR Norway development was put out to tender won by NORCE and their subcontractor PPO.Labs who began developing the system in 2016 in close collaboration with NGU and the Norwegian Space Agency. In the first years of the development phase from 2016 to 2019, InSAR Norway has been funded approximately 70 % by the Norwegian Space Agency through the Norwegian national Copernicus programme, and 30 % by NGU/NVE. In the next, more operational

[26] Space for smarter infrastructure – Dag Anders Moldestad

phase in 2020 and 2021, the funding partnership will be 50 % Norwegian Space Agency and 50 % NGU/NVE.

The first dataset was released in November 2018, covering all mainland Norway including the islands along the coast. Only data from months with little snow cover are used, that is, June to October, to minimise inaccuracies with the measurements due to the presence of snow. The dataset is updated once every year, during the autumn, when all data from the summer have been acquired. As the service continues to develop, some areas will be updated more frequently, especially urban areas.

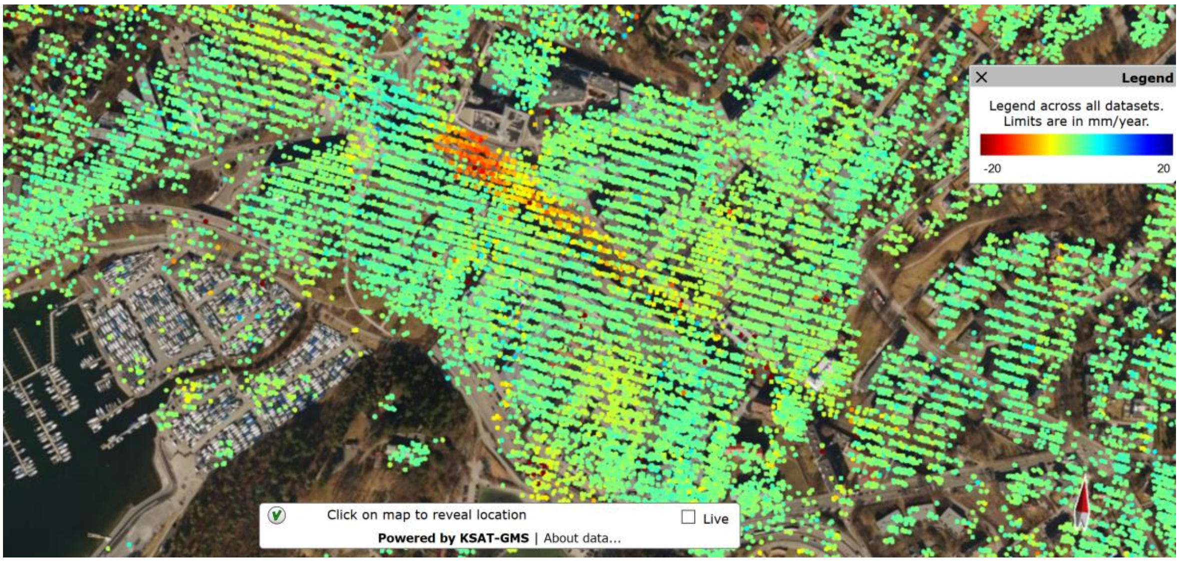

Figure 3-7: Ground motion over the west of Oslo

The spatial resolution for Sentinel-1 is approximately 5 x 20 metres (5 metres in the east-west and 20 metres in the north-south direction). The user can access any area within Norway, and the subsidence is shown as coloured points on the map. Figure 3-7 and Figure 3-8 show extracts from the database for two areas in Oslo showing ground motion.

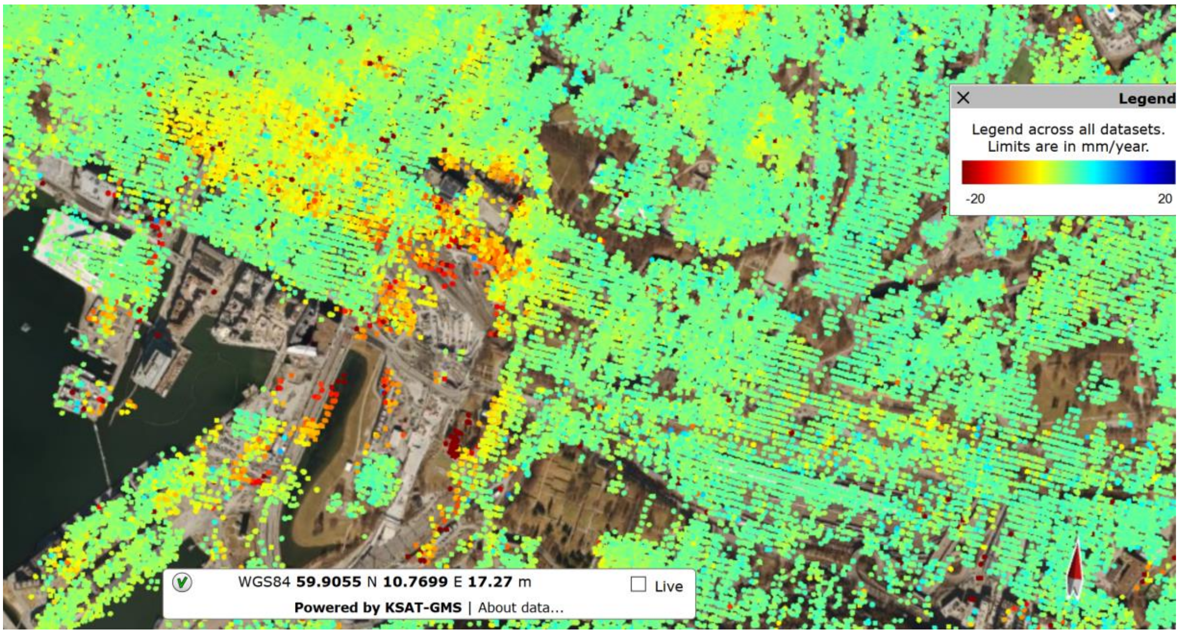

Figure 3-8: Ground motion over the Bjørvika site in Oslo.

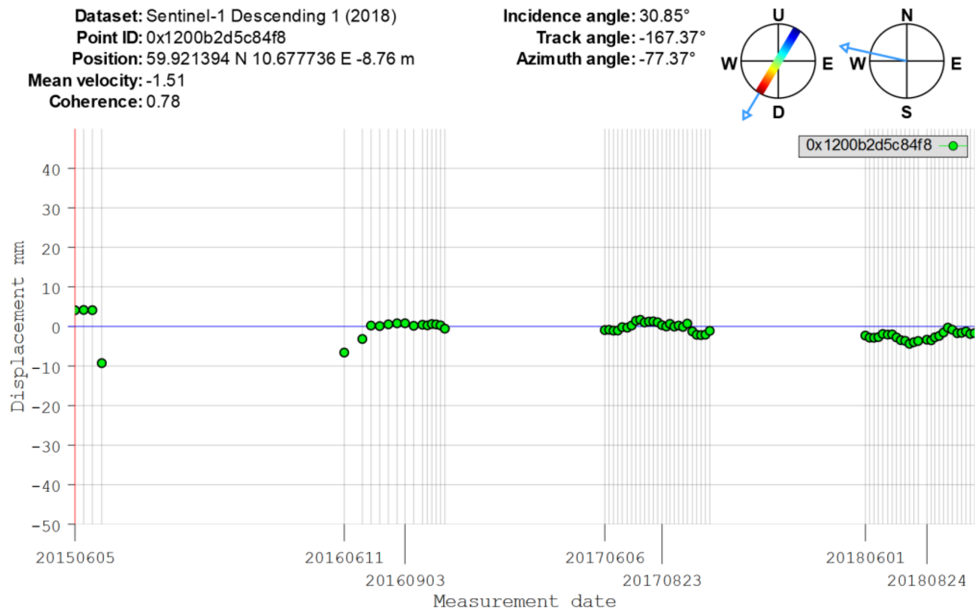

Figure 3-9: Time series of measurements from 2015 to 2018, showing a stable ground surface.

The Sentinel-1 satellites pass over Norway along the same orbit every six days. Each of the passes is processed, as can be seen in Figure 3-9. This chart is generated for a single "dot" in the ground motion map and shows how that point has moved over time.

The point selected in Figure 3-9 is rather stable, but if we select a red dot from the Bjørvika image, we can see the extent of the motion over time (Figure 3-10). Between 2015 and 2018, the point has sunk by approximately 5 cm, having an average subsidence of 14 mm per year. This allows correlation with local works to identify if there is a link with any construction or climatic effects.

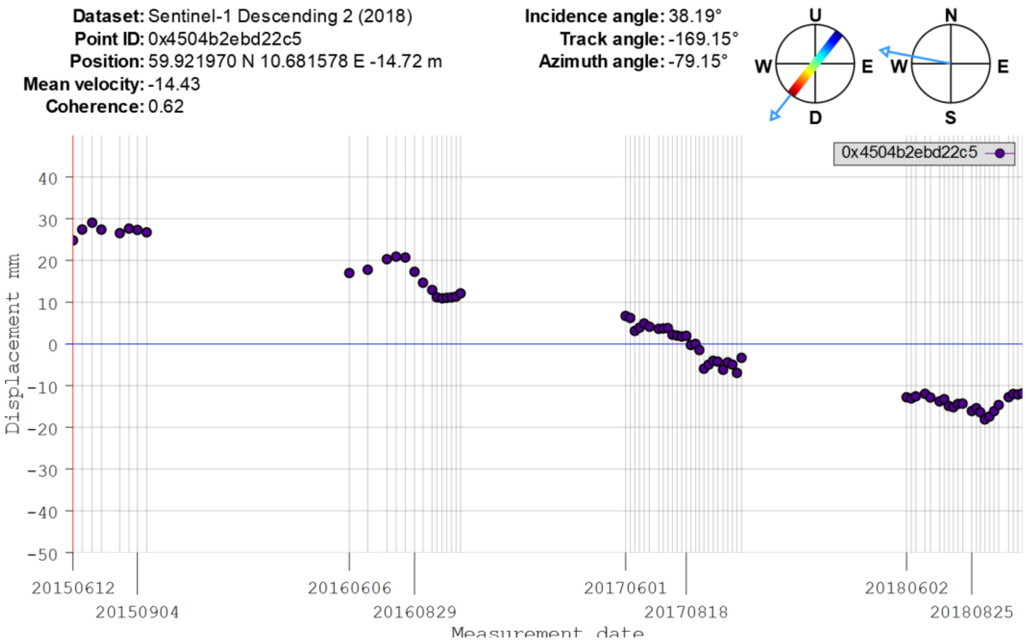

Figure 3-10: Time series of measurements from 2015 to 2018, showing sinking ground.

3.5 Evolution of the service

Using software developed by NORCE, PPO. Labs, the Geological Survey of Norway (NGU), the Norwegian Water Resources and Energy Directorate (NVE) and the Norwegian Space Agency, the Norwegian Ground Motion Service, or “InSAR Norway” was officially launched in 2018. Using images acquired four to eight times a week over Norway by the European Copernicus Programme Sentinel-1A and B satellites, it can now measure and continuously monitor all movements to within one millimetre per year at more than three and a half billion locations across Norway.

The ground motion map is currently updated once per year under the standard, free and open, service. More frequent updates are planned as the service develops, especially in urban areas. As most of Norway is covered with snow during the winter, the service currently uses only images acquired between June and October, for the entire country. As the service evolves, the processing will be adapted to local climate conditions to maximise the number of scenes used at all locations.

In urban areas, a better spatial resolution may be desirable to distinguish the precise location of movements. With Sentinel-1, the exact location of a measurement point can only be determined with approximately five metres precision. For some applications, this may not be sufficient to determine exactly which part of a structure is deforming. In that case, higher spatial resolution, commercial SAR data will be needed. It remains to see whether the cost of the commercial satellite imagery might be a limiting factor, but, as shown by InSAR Norway, the cost of not knowing about the movements may be many times higher.

3.6 The Norwegian Avalanche Warning Service

As will be explained in the next chapter, this report contains two value chains, the primary value chain is concerned with the development of the Norwegian road network while the second value chain involves a rock slide monitoring service. **In undertaking our analysis, the provision of a third service, which also uses Sentinel data and has proven to be invaluable to the NPRA is an avalanche monitoring and warning service.** Although this service doesn't fit neatly into the primary or secondary value chains, it is worth noting that Sentinel data is being used in a third application and that demonstrable benefits are stemming from its use.

The service is called the "Norwegian Avalanche Warning Service". It uses Sentinel-1 data to detect snow avalanches and monitor avalanche activity in all avalanche-prone areas in Norway. The automatic avalanche detection and monitoring service has been developed in a collaboration project between the Norwegian Water Resources and Energy Directorate (NVE), the Norwegian Space Agency, NPRA and NORCE, and will be used operationally by NVE[27] with NORCE as their development partner. NVE is responsible for issuing public avalanche forecasts in Norway. The service is at present operational for four avalanche forecasting regions in Norway and will be scaled to all avalanche-prone areas in Norway in 2020. The avalanche warning service is also used by the NPRA, and hence we have included it briefly within this report.

The avalanche warning service was launched in 2013[28] with the main goal of the service being the avoidance of accidents and reduction of traffic problems due to avalanches. According to varsom.no (where the service is hosted): "*The main user groups are within recreational winter sports, road and railroad authorities and emergency authorities. The bulletins and forecasts are important tools for evaluating the snow avalanche conditions, but do not provide the correct answer for every snow-covered slope.*" The forecasting service identifies the areas at risk as shown in Figure 3-11.

Sentinel-1 data is used to detect the difference in backscatter, between snow-covered surfaces with and without an avalanche. Where an avalanche has occurred, the roughness of the snow cover changes thus giving a larger backscatter signal than from the original snow-covered surface without an avalanche. Comparing images taken at each pass, allows avalanches to be detected.

[27] https://eo4society.esa.int/2019/03/19/snow-avalanche-detection-and-monitoring-with-sentinel-1/

[28] https://www.varsom.no/en/avalanche-bulletins/about-the-norwegian-avalanche-warning-service/?ref=mainmenu

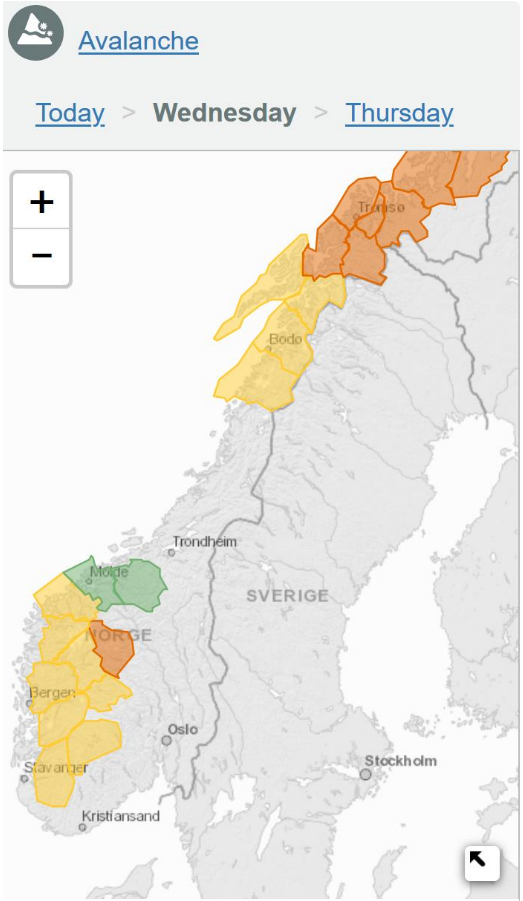

Figure 3-11: Avalanche forecasting service offered by NVE.

Comparing automatic detections to manual interpretations, the algorithm achieves probabilities of detection (PODs) between 82 % and 55.7 %. Corresponding false alarm rates (FARs) range between 26.4 % and 13.8 % (Eckerstorfer et al., 2018). The variation in sensitivity stems from the algorithm's dependency on snow conditions in the change detection images.

Comparing the accuracy of the automatic algorithm to *in situ* observations of avalanches, the achieved POD is 61.6 %. However, the algorithm was capable of detecting all avalanches in the *in-situ* dataset that were large (capable of destroying a house) and 90 % of all medium-sized avalanches (capable of burying a car). Nevertheless, only roughly 30 % of all small avalanches (capable of burying a person) were detected.

The NPRA is heavily involved in this service for two reasons:

- In conjunction with NVE, the NPRA and the Norwegian Meteorological Institute (Meteorologisk Institutt) help provide the service.
- The NPRA also acts as one of the most prominent primary users of the service.

With regards to the second point, the NPRA uses the avalanche warning service to help them make better operational decisions when it comes to closing and opening roads pre and post avalanche events. This enables them to keep the public safe while maintaining road operations in as efficient manner as possible. The service is also used by the NPRA to identify risk areas that should be taken into account when planning new road infrastructure developments.

4 Understanding the Value Chains

4.1 Description of the Value-Chains

This case actually provides us with two value chains. The primary value chain, which will be focussed on more heavily, involves NORCE and PPO.Labs (with funding from NGU, NVE and the Norwegian Space Agency) developing the Norwegian Ground Motion Service, which the Norwegian Public Roads Administration (NPRA) use in their planning, construction, and operation of the Norwegian road network. Actors further along this primary value chain include construction and engineering companies, as well as the rail authority of Norway and, ultimately, all road users. A visual representation of the primary value chain is presented in Figure 4-1 below:

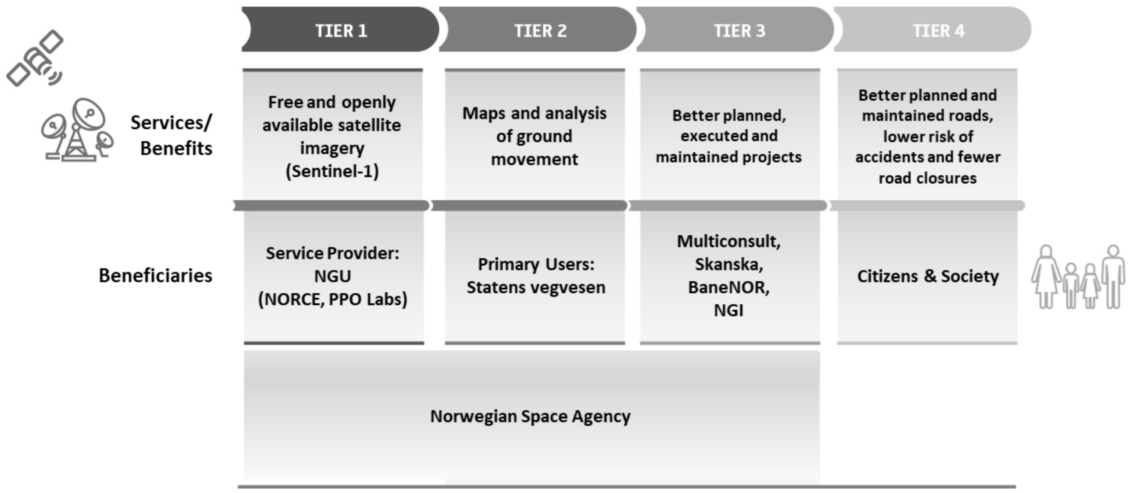

Figure 4-1: The Primary Value-chain

The secondary value chain, in this case, involves NGU using the Norwegian Ground Motion Service themselves to help them in their role of identifying and classifying areas where rock slides could potentially be an issue. A visual representation of the secondary value chain is presented in Figure 4-2 below.

Finally, the **Norwegian Avalanche Warning Service** will be considered and discussed as an additional value creating entity on its own. However, a full value chain for this service will not be described or analysed.

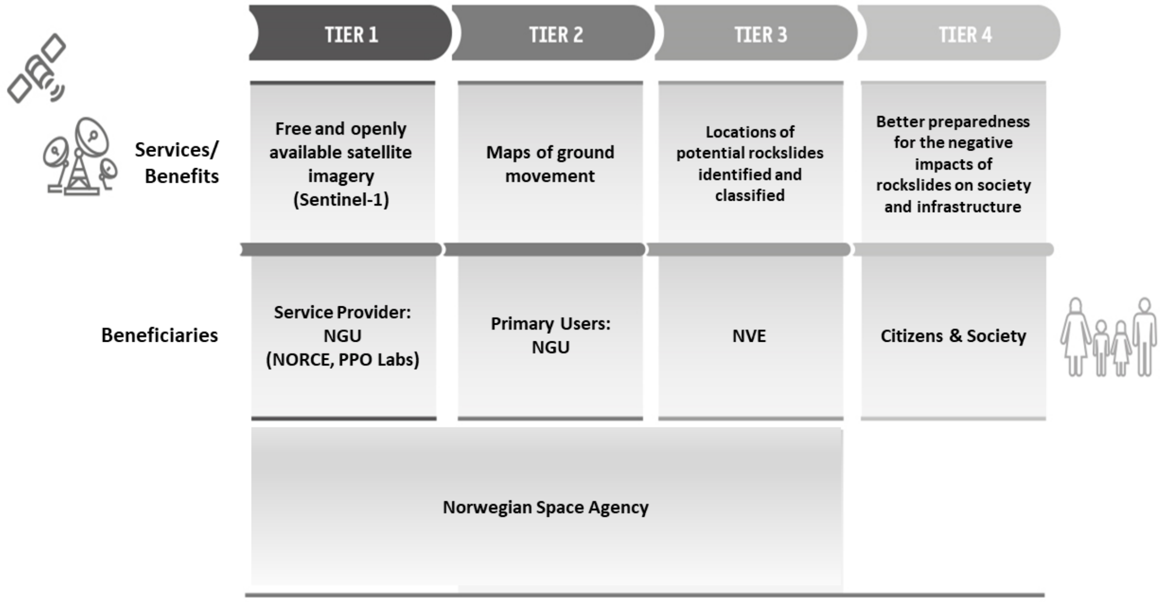

Figure 4-2: The Secondary Value-chain

4.2 Actors in the primary value chain

4.2.1 Tier 1: Service Provider – NGU and partners

The development and maintenance of the InSAR Norway system is made by NORCE, a Norwegian research institute and PPO Labs, a technology company based in The Netherlands. The project was commissioned and is funded by a number of government bodies and organisations: The Geological Survey of Norway (NGU), The Norwegian Water Resources and Energy Directorate (NVE), and The Norwegian Space Agency. NGU operates the service.

NGU is uniquely positioned as a service provider. They are not only one of the key instigators and funders of the project, but they also play a key role in the use of the service itself. Being the government agency responsible for the knowledge of bedrock, mineral resources, surficial deposits, and groundwater, one of NGU's responsibilities is to identify and classify areas that are at high risk of dangerous ground motion. NGU together with the Norwegian Space Agency, NORCE and PPO.Labs, therefore, played a vital role in deciding how the InSAR Norway service should look like and feel, as well as what functionality it should possess. In their rock slide identification and risk classification role, the InSAR Norway service is now NGU's primary tool in surveying the vast landscapes of Norway for areas in which the ground is accelerating at dangerous speeds.

NORCE, a not-for-profit research organisation, was contracted to develop the InSAR Norway map. In their operations, they, in turn, contracted PPO Labs to help in the development of the service. Although online since 2018, the service's development phase runs from 2016-2021, allowing NORCE to expand its functionality and take user feedback onboard, with a view to develop the most user friendly and functional service possible. During development, NORCE has overseen the updates of over three and a half billion data points, spanning the entire terrain of Norway. Over the next year, the production role will be transferred to the operator, NGU.

4.2.2 Tier 2: Primary User – Statens vegvesen (NPRA)

Statens vegvesen (The Norwegian Public Roads Administration, NPRA) is the government agency responsible for national roads in Norway. They plan, build, operate and maintain roads and are responsible for developing technical regulations for all roads in Norway. The NPRA also are responsible for driver tests and inspection of vehicles and road users. Founded in 1864 and headquartered in Oslo, they currently employ about 6000 people. The organisation consists of a Directorate of Public Roads and five divisions. A recent reorganisation has the Norwegian counties looking after their own regional roads whilst the NPRA remains in charge of the major, national roads.

When it comes to planning, building, and maintaining the public road network in Norway, as already discussed, ground stability is of major concern. This makes the Norwegian Ground Motion Service an invaluable tool to the NPRA. The data provided by the InSAR Norway map can be referenced and interrogated from the very conception of any project right through to the development phase, the maintenance phase, and beyond. Engineers within the NPRA are actively using the InSAR Norway map as their primary reference point when trying to understand if there are any areas of terrain which should be of concern to their operations. In the planning phase, the map can be consulted to get an overall picture of the quality of the land upon which groundworks may potentially go. The historical data archive capabilities of the service are particularly useful at this stage as they can give an idea of how the terrain in any region behaves over the medium term. This will only get more and more useful as the service matures and gathers an even more long term and comprehensive understanding of Norwegian ground behaviour.

Furthermore, in the building and maintenance phases, the map is being used to keep an eye on how road works are affecting ground stability and has proved useful in drawing the attention of engineers to areas that may be experiencing subsidence. Once problematic areas have been identified, engineers can then scrutinise the ground motion in that area in greater detail. It is in this role, of providing an overview of any region in the country and identifying potentially dangerous instances of ground deformation, where the InSAR Norway map really manifests its value. Although the Sentinel data used in the generation of the map are not the highest spatial resolution available, the NPRA has been actively using it to help identify areas that may be of concern, triggering the need for them to conduct further detailed analyses. Being so impressed with the accessibility and usefulness of the InSAR Norway map, the NPRA has recommended its use in their regularly updated "handbooks." These handbooks are published by the NPRA and provide planning and engineering guidelines to all road construction and planning organisations in Norway.

4.2.3 Tier 3: Construction and related industries

The tertiary beneficiaries, in this case, are actors involved in road construction activities. All construction actors who are contracted to do work on Statens vegvesen projects are inherently passed some of the benefits experienced at Tier 2, simply by virtue of the fact that they are working on better planned and monitored projects. Better planned and monitored road infrastructure projects avoid delays and safety breaches as well as structural or technical issues. These benefits can, therefore, be felt at both customer and client levels. However, in this case, the construction and engineering companies themselves also direct users of the InSAR Norway map and Sentinel based services to conduct their operations more effectively.

Although there are numerous geotechnical, engineering, and construction companies that get involved in NPRA projects, as well as other government agencies who have overlap with NPRA projects, the following four organisations have been interviewed about their relationship with the NPRA: Multiconsult, Skanska, BaneNOR and NGI. Their roles in the value chain are discussed below.

Multiconsult, a Norwegian engineering consultancy company headquartered in Oslo but with multiple offices throughout the country is just one of a number of companies that conduct road infrastructure projects. Multiconsult can undertake operations at any stage of a project's lifecycle, from planning and surveying to engineering and construction. Depending on how wide-reaching their responsibilities are in a given road infrastructure project, they can utilise the Norwegian Ground Motion Service, InSAR Norway, in different ways.

Harald Øverli Eriksen, a specialist in geology and remote sensing who works at Multiconsult, has noted[29] that at the planning stage, the InSAR Norway map can be consulted to alert them to any potential subsidence issues they should be aware of in the area. At the construction phase, the map can be used to keep an eye on how groundwork activities are both progressing and how they are impacting the earth around them. In the previously mentioned case of the bridge construction at Sifjord, Multiconsult has also specifically contracted NORCE to provide them with higher frequency updates on certain points along the bridge's foundation. In order to measure settlement and subsidence of the bridge's foundations and filling rock, Multiconsult installed what are known as "corner reflectors" on top of the foundations. Corner reflectors allow a strong and definite InSAR signal from a specific point on earth to be picked up by Sentinel-1 and can be installed at strategic points along foundations. Settlement of the filling rubble is required before further construction work can begin on top. With the help of Sentinel-1, this settlement can be measured remotely, continuously, and accurately.

[29] Multiconsult: subsidence monitoring of fjord crossing.

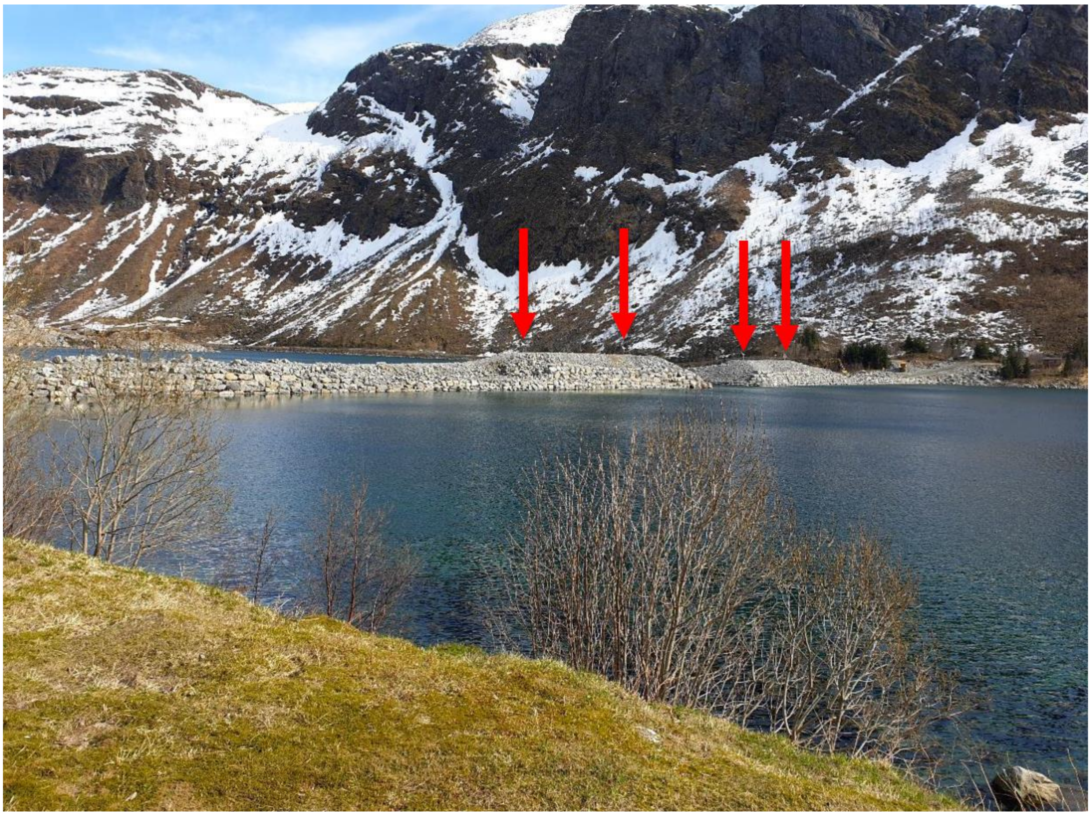

Figure 4-3: The bridge foundations at Sifjord with corner reflector positions indicated

Figure 4-4: A corner reflector installed on the foundations

Skanska AB is a multinational construction and development company based in Sweden who operates extensively in Norway. Skanska works in many sectors, including commercial property development and housing, as well as public infrastructure projects. They currently are involved in around 150 ongoing projects in Norway. Similar to Multiconsult, Skanska is involved in a number of projects with the NPRA and has also begun looking into the use of the InSAR Norway map. Although they are in the early stages of using the Norwegian Ground Motion Service, Skanska is testing the service as part of one of their NPRA related projects in the Ålesund region of western Norway. Comprising of a typical Norwegian landscape of fjords and islands, the Ålesund region is currently undergoing a road infrastructure upgrade which endeavours to improve the connections between a number of the islands. Skanska is involved in this project and is using it to test the use of the InSAR Norway map. They are comparing their own in situ data to the data from the InSAR Norway map in conjunction with some further scrutinised data points which NORCE is providing them. Lars Horn, an engineer at Skanska, has noted that should they be satisfied with the results, they feel they can really begin to move forward with more widespread use of the service throughout their organisation. He also noted that in the acquisition of land and planning of projects, the InSAR Norway map is indeed consulted and has been proven to be useful in gaining an understanding of the historical behaviour of the terrain in a given area.

BaneNOR is the Norwegian government agency responsible for owning, maintaining, operating, and developing the Norwegian railway network. BaneNOR comes under the responsibility of the Norwegian Ministry of Transport and Communications. Engineers in BaneNOR have already begun referencing the Norwegian InSAR map when undertaking railway infrastructure projects. However, the use of the service within BaneNOR is only in its infancy. BaneNOR does, however, experience some of the benefits of the ground motion service as a result of their close relationship with the NPRA. Multiple NPRA projects have intersection points with BaneNOR projects as quite often road infrastructure development projects go hand in hand with rail infrastructure projects. The previously mentioned case of the railway infrastructure development in Fredrikstad, which had to be suspended, is an example of the close working relationship between the NPRA and BaneNOR. It is exactly these types of relationships, where actors like BaneNOR, who's own infrastructure projects have multiple contact points with some of the NPRA's projects, that showcase how tertiary actors are both affected and can benefit from improved planning and maintenance operations in the NPRA.

The Norwegian Geotechnical Institute (NGI) is a private commercial foundation which conduct geotechnical analysis on construction and infrastructure projects for both private and public clients. NGI performs risk mapping of urban areas for the NPRA and is involved in a number of their road infrastructure projects. Regula Frauenfelder, a Principal Engineer working with NGI in Oslo, noted that they see their production of ground deformation maps based on very high-resolution commercial satellite data, their geotechnical expertise, and their data analysis capabilities as what sets their services apart from the Norwegian Ground Motion Service. Sentinel-1 based InSAR maps will not offer the same measurement point density as deformation maps based on very high-resolution commercial satellite data, given the same quality of InSAR algorithms and methods and performed by the same InSAR service provider.

Regula recognises that the InSAR Norway map can be of use to their operations. When needing a consistent reference source, which spans the entire country and can be easily accessed and interrogated, the InSAR Norway map is a starting point for NGI to provide an overview of any given area in the country. It helps NGI identify regions of interest, which can then be further scrutinised by their technicians. The map is at present essentially used as a free source of data to help them trigger further analysis. Nevertheless, Regula also observed that, as a freely-available, public service, it has also displaced some of the business of NGI and it remains to be seen, for NGI at least, if the positive impacts will outweigh the negative ones.

4.2.4 Tier 4: Road users, citizens, and society

The final tier in the primary value chain of this case involves all road users and citizens who reap the benefits of having better planned, better maintained and safer roads. Having well-connected cities, ports, and regions can help boost the economy of a country, as it reduces non-tariff barriers to trade. A well-developed road network encourages the easier and swifter transport of people, capital and goods, thereby stimulating business and economic activity.

The most obvious beneficiaries of better roads are freight companies, transport companies, and corporations who move large volumes of goods and capital to and from different locations. They can reduce operating costs due to shorter travel times and more efficient fuel use. However, high-quality road infrastructure allows for the emergence and success of modern supply chain management, affecting an enormous number of stakeholders, from huge commercial companies right down to individual citizens.

In a “Partners for Roads” initiative, the Dutch Directorate for Traffic and Infrastructure measured the impact of roads on regional economies in the Netherlands. The study clearly demonstrated that zones with high job densities (over 200 jobs per square kilometre) were systematically located near major road arteries[30] as industries prefer to have easy access to their suppliers, customers, and employees.

A study in Spain looked at the economic benefits of the construction of the A92 motorway in the south of the country. Overall, it found that over 30 years, the benefits reached a massive €39.9 billion, constituted mainly by road users saving time by undertaking shorter journeys, reducing congestion, and lowering the prevalence of traffic accidents. The project itself cost €11-12 billion, thereby providing society with a net gain of almost €28 billion. Better roads can improve a number of social factors too, including the previously mentioned reductions in traffic congestion, decreasing

[30] “Partners for Roads – Roads and Regional Development”, Presentation delivered at the European Road Congress (Lisbon, Nov. 2004) by Mr. Michel Goppel, M.Sc and Mr. Benno Bultink, Directorate for Traffic and Infrastructure, The Netherlands

the number of road accidents and fatalities, as well as increasing access to education and health care while reducing CO_2 emissions[31].

4.3 Actors in the secondary value chain

4.3.1 Tier 1: Service Provider – NGU and partners

Once again, the same government bodies and organisations that constituted the service provider in the primary value chain also make up the first tier of this value chain. They are; The Geological Survey of Norway (NGU), The Norwegian Water Resources and Energy Directorate (NVE), and The Norwegian Space Agency, NORCE, and PPO Labs.

4.3.2 Tier 2: Primary User – NGU

NGU uses the InSAR Norway map themselves to help them identify areas all across the country where ground motion is accelerating at paces that could potentially lead to catastrophic rock slides. NGU is responsible for identifying these areas and classifying them into categories, from low to high risk.

Fear of catastrophic rock slides in Norway goes back several centuries. In 1934 a large rockslide in Tafjord[32] created a tsunami that killed 40 people. Similarly, 135 people were killed in large rock slides creating tsunamis at the Lovatnet lake in 1905 and 1936. Over the years, hundreds of lives have been lost in similar events. NGU is currently tasked to map potential rock slides throughout the country. It is a difficult process as mountainsides can move several centimetres per year and may continue to do so for many thousands of years without any catastrophic rock slide occurring.

4.3.3 Tier 3: NVE

The Norwegian Water Resources and Energy Directorate (NVE) take the findings of NGU's rock slide identification and categorisation work and apply more "hands-on" mitigation measures to areas which are deemed high risk. NVE is responsible for monitoring and mitigating against a number of potential natural disasters in Norway, such as floods, and since 2009 have also been responsible for rock slides. Once high-risk areas have been identified by NGU, NVE will conduct more detailed analysis and monitoring of the ground in that area as well as implementing preparation works designed to help alleviate the effects of a rock slide.

[31] "The socio-economic benefits of roads in Europe", https://www.aecarretera.com/cdc/ERF_Los%20beneficios%20socioeconomicos%20de%20las%20carreteras%20en%20Europa.pdf

[32] https://en.wikipedia.org/wiki/Tafjord

Detecting the moment when a mountainside may collapse is complex, meaning NVE has to use many different techniques for monitoring, including extensive in-situ monitoring for the most likely threats. The ground motion map was developed in close collaboration with NGU so that it could be added to their armoury of tools to monitor for potential landslides. Currently, NVE is monitoring 16 – 17 areas across the country that were identified by NGU.

4.3.4 Tier 4: Citizens & society

The final beneficiaries in this secondary value chain are the citizens and society of Norway. With NGU and NVE being able to keep a constant close eye on potentially disastrous rock slide events, citizens benefit from the fact that earlier warnings and more effective mitigation measures will help reduce the damage and destruction caused by rock slides.

4.4 Additional applications – The Norwegian Avalanche Warning Service

It is worth repeating at this point that NVE is also responsible for providing and hosting the "Norwegian Avalanche Warning Service," as discussed in section 3.6 of this report. On a daily basis during winter, the likelihood of triggering an avalanche of a certain size (consequence) and the spatial distribution of avalanche-prone areas are assessed and made publicly available.

The NPRA is highly involved in this service as they help fund it and also act as one of its primary users. The service helps the NPRA make better-informed decisions when it comes to road closures and risks associated with avalanches. The avalanche warning service is a separate entity relative to the rock slide monitoring service and cannot be fitted neatly into the primary or secondary value chain. However, mentioning it here emphasises the fact that many operational services, which benefit the public, have been borne from the use of Sentinel data in Norway.

There are over 2000 avalanches each year along roads in Norway comprising snowfalls, slush, rocks, and ice. Around one-third of the avalanches lead to road closures, which may last from one hour to several days. Some roads are closed if a high risk is identified. The service allows road users to be aware of risks and for contractors to judge when it is safe to send in machinery to clear the road.

This can have a high societal value as well as an economic one. For example, the salmon industry ships from the west coast to other ports on the Baltic or other transport points. A load is carried in a refrigerated lorry that has a transit time that extends to around 10 hours. If a lorry must turn-around and return due to a road closure, the complete load may be lost with a very high economic cost.

5 Assessing the Benefits

In this chapter, we look at the benefits which are obtained by using the Sentinel-1 derived ground motion maps for two specific value chains. Each tier in the value chain is evaluated, given the different nature of decision-making stemming from the use in different phases of road construction and operational management.

5.1 Overview

Several factors considered within the analysis of the benefits, distinguish the case of road management in Norway from previous SeBS cases:

a) The nature of the use of the Sentinel derived product

Two approaches have been found for analysing SeBS cases:

- Operational-based cases where the use of the service is routine and continuous, possibly on a daily basis.
- Project-based cases which are driven by events and, being discrete and sometimes even singular in nature, are harder to calculate the benefits for.

For road infrastructure management, both types exist depending on the phase of the activity. Our focus has been on the design and construction phases rather than the operational/maintenance phase, hence the analysis is indeed made more difficult by the project-based nature of the work, which leads to a wide variation in the impacts, the costs, and the benefits.

In this case, we take the single service which can be applied to different decision-making processes within NPRA and the other organisations concerned. Since road construction is the main activity being considered, the analysis is heavily project-based.

b) The use of a second, Sentinel-derived service by the primary user

In addition to the ground motion service, the NPRA also use the "Norwegian Avalanche Warning Service," which was co-developed along with NVE to detect and forecast avalanches. This service uses Sentinel-1 data to identify where avalanches have occurred and the information is used to provide a country-wide forecast of avalanches. The service is used by the NPRA to identify risk areas that should be taken into account when planning new road infrastructure works. The forecast service is also used by NPRA to help make better-informed decisions regarding when roads should be closed in winter due to avalanche risk or when deciding whether a road may be re-opened following an avalanche.

c) The consideration of a second value-chain

The ground motion service has also been developed by NGU for use in their rock slide mapping duties. The map has then been recognised as a service that can benefit many users in Norway with differing applications. When looking at the range of uses, we identified roads management as being of high interest for two reasons:

- The NPRA is highly concerned with rock slides and tsunamis affecting their infrastructure and operations
- The links that can potentially be made to a similar application in Italy[33].

Nevertheless, since the first application is of key interest to the NGU, we shall also consider the value chain and the benefits which are being developed, but less from an economic dimension and more about the story of its use.

d) Assessment of six dimensions of value

This will be one of the first cases where consideration will be given to the benefits along six dimensions. We take into consideration not only the economic benefits but also benefits in the other dimensions, i.e., environment, societal, regulatory, entrepreneurship, and scientific (see Annex 2).

5.2 The Primary Value-Chain

5.2.1 Tier 1: Service Provider – NGU and partners

NGU

NGU benefits directly from the ground motion service by having a service that can directly contribute to their mandated role while also supporting other sectors and applications. Further explanation on the benefits for NGU is provided in section 5.2.3.

NORCE & PPO.Labs

NORCE, with the support of the Dutch company PPO.Labs, are the parties developing the algorithms and software at the core of the ground motion service. NORCE, a not-for-profit research organisation whose majority shares belong to four Norwegian universities, reinvests all revenues from commercial activities (such as the development of this service) in R&D. The knowledge and experience gained through the development of this service for NGU advances the scientific positioning of NORCE in Europe and sparks new developments that can be further commercialized. NORCE and other players such as NGI and KSAT, are also able to generate new (spillover) business based on the annual ground motion maps since customers are wanting more frequent measurements over local sites – which is possible using the Sentinel-1 data – and in some cases using commercial data to produce maps with a finer spatial resultion on the ground. This creates a sustainable cycle of knowledge development and knowledge application, benefiting the financial stability of NORCE and of its employees.

In the context of InSAR Norway, the relationship between NGU, NORCE and PPO.Labs, is part of a well-structured ecosystem from which also industry benefits. KSAT has, for instance, a close

[33] SeBS case study: Highways Management in Italy; awaiting publication

working relationship with NORCE and draws knowledge and expertise by recruiting highly qualified NORCE employees. Other companies in Norway have also recruited internationally recognized experts from NORCE, directly benefiting from their knowledge developed while at NORCE.

NORCE is benefiting from the knowledge gained from the InSAR processing for NGU to help their scientific research. The knowledge gained has helped NORCE develop new products and services. Their close links with Multiconsult has led to a new service focused on landfill monitoring.

Does the presence of a university-linked not-for-profit organisation in the value chain crowd out other commercial developments? Both NORCE and NGU have "not-for-profit" status, and through discussions with commercial companies along the value chain, this was generally seen as at least not being negative. Many companies work with both NORCE and NGU, for example, KSAT has a close working relationship with NORCE and recruit trained staff as a result, whilst Multiconsult has also recruited ex-NORCE engineers to work in-house. Therefore, this symbiotic relationship seems to work well, with the local ecosystem benefitting from the NORCE and NGU relationship, whilst not crowding out business initiatives.

One example of NORCE generating new business based on the annual ground movement map is the monitoring of ground stability for Multiconsult where NORCE provide not only the service but also the corner reflectors which were used. The experience gained by NORCE through the development of the InSAR Norway service for NGU will also enable them to offer similar services to other customers. For instance, a European-wide ground motion service is being constructed and NORCE will be able to position itself as a Norwegian partner for its supply.

The Tier 1 benefits are summarised in the table below.

Summary of Tier 1 benefits	€/year in Norway
Symbiotic relationship between NGU and NORCE encouraging value creation	**N/A** – Will remain reported as a qualitative benefit in this case

5.2.2 Tier 2: Primary User – NPRA

The use of InSAR by the NPRA has so far been limited to a few projects. These differ in that some projects have made use of the InSAR Norway service while for other projects, it is apparent how the project could have evolved better had the InSAR Norway service been used (if it would have been available). As awareness and understanding of the technology becomes more widely known, and the cases become more frequent, it is anticipated that the maps will be used more, and direct benefits will be more apparent than they are today.

Wider use of the maps is expected since NPRA produces handbooks of practices to be used by road agencies throughout Norway. In some cases, these are regional departments of the NPRA, but things are changing as responsibility is being delegated down to the county level. However, NPRA maintains the overall reference of good practices which parties in the road management and road building sector are obliged to follow. In this way, knowledge of the use of the ground mapping service and of InSAR more broadly is being disseminated.

In discussions with NPRA, we identified a number of ways in which InSAR has been used (or may be used in the future):

1. **At the design and planning phase:**
    - It can offer better, more accurate surveying technology which can reduce project related survey costs.
    - It can also be an important tool for detecting areas of risk, at an early planning stage, which helps to avoid potential issues in the future.
2. **At the operational phase of road projects it can be used to determine risk and damage to current infrastructure**

Not all of these are at the same level of maturity, and research is continuing into their application and degree of importance to NPRA. The bullet points above will be describe below in more detail.

1 - Benefits at the design phase: Improved surveying reducing project related surveying costs

Traditional engineering surveys are required to assess the area of the proposed works as part of the prior decision making for the project investment. They will cover the topography, the underlying geology, the type of land, and any constructions (houses, drainage, etc.) which exist. They do not generally provide information on the ground stability, and if this is required, will demand a significant investment into augmentation through a locally installed measuring network. In general, this is because the use of satellite, location-based services, i.e., GNSS, does not enable precise height measurements (it is very precise in location, x and y, on the earth's surface but not in the third dimension, z), hence it is quite unreliable if the ground motion is to be measured or even detected[34].

Ground motion may be caused by several different factors; geological instability near the surface, or tectonics such as earthquakes. Knowing if there has been a history of motion in the site or if there is current motion of the ground can help save significant costs later. It is worth adding that motion may also be triggered by actions during the construction phase of the project – but this will be considered later.

At this point, it may be helpful to make a reminder of the different ways in which Sentinel 1 data is being used. The national ground motion service on which this case is based provides a complete map and time series of ground motion across Norway on an annual basis (see chapter 3.3). However, the Sentinel data is available much more frequently - about one image every two days in Southern Norway - which allows specific sites to be updated more frequently.

Prior to the use of InSAR Norway, the likelihood problems arising with road infrastructure projects was higher. Satellite based data has clear benefits with respect to:

[34] Cost benefit analysis of a proactive geotechnical asset management system using remote sensing – Michigan Technological University: https://mtri.org/geoasset/media/doc/deliverable_Deliverable%206A.pdf

- Subsidence and uplift caused by ground motion can be mapped with accurate vertical precision.
- Historical data using archived SAR imagery can show past ground motion, which is not possible using traditional surveying.

Hence, the use of InSAR can improve the precision of measurements, thereby improving the engineering design and reducing the risk of additional costs being incurred later in the project. It can also reduce surveying costs for those projects where past or existing ground instability is known or suspected.

With regards to the first point, we will discuss how improved surveying can benefit the NPRA in the design phase of their projects. However, the most concrete example of this benefit comes from our discussion with Multiconsult, who used InSAR in a project to monitor the foundations for the new bridge at Sifjord. The benefit, in that case, fell mainly during the construction phase of that project. Therefore, we shall consider it in the analysis of Tier 3.

With regard to the availability of historical data from the Sentinels, this benefit is clearly exemplified in the case of the Tønsberg tunnel. Once engineers involved in the project used the InSAR Norway map, they could immediately see that the ground at the eastern end of the tunnel was very unstable. Thanks to the available historical data, they could also see that this was not a new phenomenon, and the ground had been in poor condition for at least a few years. The fact that this subsidence had most likely been going on for quite a while meant that it wasn't something that happened post-project and, in theory, could have been picked up on during the design or construction phase. Knowing this kind of information is extremely useful for any civil or structural engineering project, and had it been known by engineers prior to the construction of the tunnel, remedial action could have been taken, saving time and money.

The benefits in the case of Tønsberg example are twofold:

1. **The cost of surveying and subsequently monitoring of the site:** In reality, the large extent of the ground motion is such that any survey around the tunnel would not have detected that the whole area down to the waterfront is moving (see Figure 2-8) and hence we cannot really make a cost comparison as the survey would never have been made in the first place. Now that the ground motion map is available regularly (annual) and on a large scale, such instability is easily detected and localised surveys conducted if needed – possibly using more frequent updated and current InSAR data.
2. **Had the map been available at the time of the design of the Frodeåsen tunnel, the information would have been used to design a different form of construction:** This would have avoided the costs of remedial works. So, the economic benefit of the use of the map is the avoidance of the costs of the remedial work. We shall make some calculation of this cost and hence economic benefit under the next section.

In order to quantify some of the benefits of reduced survey costs at the "design" phase of projects, we can make the following assumptions:

- Using traditional methods, the accuracy of vertical measurements is considerably less than using InSAR over large areas. (It must be noted that the use of in-situ measurement or “levelling” can be slightly more accurate in certain situations, for example at smaller scales i.e. scales below 100m x 100m or when much larger movements are occurring i.e. cm/week accelerations). Even the use of GNSS will not give much improvement in measuring a vertical displacement[34]. A local augmentation system will need to be set up to provide equivalent measurement accuracy. We will assume the cost of this system as €20,000 for an average project.
- In addition, a surveyor will need to go to the site to make the measurements on a regular basis. We will assume five visits are needed at the design phase of each project, with each visit taking one day. Taking a surveyor cost as €500 per day gives a cost of €2,500. This gives a total cost for “traditional” methods of surveying during the design phase as (€20,000 + €2,500) = €22,500.
- We do not have accurate figures for the cost of the contract to provide regular InSAR measurements over a given site, but in discussion with several companies supplying this type of product, we estimate that this should be around €10,000-€15,000.
- **Hence, we estimate that the economic benefit of using InSAR methods at the design phase of an average project will be between €7,500 and €12,500** (€22,500 **-** €15,000 or - €10,000).

To scale this up to an annual figure which covers the entire country, we will use the following assumption:

- The NPRA have planned around 120 medium to large road infrastructure projects over the next 12 years, giving an average of 10 projects per year. Norway is divided into ten road administration regions, therefore, we can make an assumption that each region has, on average, 1 medium to large sized project per year. We will also assume each region has at least one additional small project each year. This amounts to 20 projects per year on average. We will assume between 20% to 40% of these projects could benefit from using InSAR technology when conducting surveys at their design phase, that leaves us with an estimate of between four and eight instances of projects throughout Norway each year which could benefit from InSAR technology.
- **In total, this gives us a potential survey cost saving, at the design phase, of between €30,000/year (lower estimate) and €100,000/year (upper estimate).**

An important tool for detecting areas of risk at the planning phase

Well planned civil and structural engineering projects mean that delays and issues with construction are much less likely. It also means that the likelihood of communities being affected negatively as a result of the project is greatly reduced. When undertaking road developments and major infrastructure projects, taking every piece of available information into account before construction means that engineers can make informed decisions at each stage of the process and, therefore, execute the project to the best of their abilities. Delays in projects which can be attributed to insufficient understanding of ground quality prior to construction can cost both time and taxpayer's money. Failures in structural integrity can cause serious safety hazards for both construction workers and the public alike, meaning they should be avoided at all costs. A number of the infrastructure projects we have discussed so far either did, or could have, benefited greatly from the use of InSAR technologies at the construction phase.

Engineers involved in the construction of the Frodeåsen tunnel in Tønsberg, in particular, would have benefited hugely from having a full understanding of the poor ground conditions that spanned across quite a large area at the eastern end of the tunnel. Planning and construction work could have been approached in a different way, or design changes to the tunnel itself could have been implemented, thereby eliminating the need for the constant remedial works currently being undertaken. Not only do the structural weaknesses, bumps in the road surface, and cracks in the tunnel infrastructure cause a headache for engineers, they impact the users of the infrastructure. These failures increase the risk of injury or accident due to exposure to uneven surfaces or cabling. Numerous press articles down through the years have highlighted peoples' concerns within the community about the sinking of the infrastructure in the area. In a report written by external consultants for the NPRA, it was concluded that the costs of repairs directly related to the poor ground conditions amounted to 15 million NOK (€1.5 million) in total between 2009 and 2017[14]. This equates to an average spending of €166,666/year. In extrapolating the figure of €166,666/year to apply to the whole country, we can also make the following conservative estimation:

- As already discussed, Norway is divided into ten road administration regions. Therefore, if we make an assumption that each region has, on average, two road infrastructure projects per year, this amounts to a total of 20 projects per year. If we assume between 5% and 10% of these projects experience similar issues to Tønsberg (i.e., issues that require annual remedial works that could have been avoided by better understanding of ground conditions through the use of InSAR in the project's early stages) that leaves us with an estimate of between one and two instances of projects throughout Norway spending €166,666/year on reparation works.
- **This amounts to a total cost of between €166,666/year and €333,332/year that could have been avoided**.
- It must be noted that the counterfactual to this figure is the amount of extra money that may have been needed to be spent on altering the design or construction methods at the beginning so as to implement stronger structures, had InSAR been used in the first place. Given that the NPRA themselves have not assessed the potential counterfactual in this case, the intricacies and "unknowns" involved in doing such a calculation, and the fact that we have been very conservative in our cost saving assumptions, we are not going to calculate the counterfactual in this case.

In Fredrikstad, a railroad station and connecting infrastructure was planned in an area with poor ground conditions and significant subsidence. Subsidence is caused by a complex interaction between groundwater leakage, due to earlier construction work, and sediment compaction.

Subsidence measured at several locations in the area was confirmed by InSAR data, that shows a subsidence rate of circa 4 mm/year with no sign of termination. The use of InSAR gave an advantage in understanding the complex ground conditions and was used as a tool for prognosis of the risk area.

This project has practically come to a standstill as a result of the many issues being faced. If the understanding of the ground conditions in the planning phase had been better, the budget could have been kept and construction of the InterCity Railroad and connecting infrastructure could have been completed as planned. There are a number of press articles disputing the costs associated with the issues at Fredrikstad, ranging from 4.8 billion NOK to 29 billion NOK[35]. We will, therefore, take the lowest estimate of 4.8 billion NOK (€480 million) as a starting point. If we conservatively assume that 1% of this could have been saved by using InSAR to better understand ground conditions earlier in the construction, we arrive at a cost saving of €4.8 million for this particular project. Again, we will use the same extrapolation method as before to apply this saving to the entire country.

- As previously stated, Norway is divided into ten road administration regions. Therefore, if we make an assumption that each region has, on average, two road infrastructure projects per year, this amounts to a total of 20 projects per year.
- As the issues experienced in Fredrikstad are quite severe, not particularly common and not "annually" recurring costs, we will make the conservative assumption between 2% and 4% of the previously assumed 20 projects experience something similar to what is going at Fredrikstad every year. This equates to between 0.4 and 0.8 projects incurring €4.8 million extra costs, which could have been avoided had InSAR technology been adopted.
- **In total, we can say that costs of this kind, which could be avoided, amount to between €1.92 million/year (lower estimate) and €3.84 million/year (upper estimate) in Norway.**

The re-development of Oslo city centre and the Bjørvika district in particular has brought with it numerous ground stability issues. Oslo has nearly 3000 old brick buildings that are at risk of subsidence due to soil compaction. This often stems from changes in groundwater levels as a result of construction work. In addition to this, a lot of the older buildings in the city centre are built on wooden foundations, meaning when groundwater comes in contact with the wood it can begin to rot, leading to even more extreme displacement.[36] During construction work, the impact of the new rail and building infrastructure on the area became evident through the use of InSAR, which remains a very useful tool in the continued monitoring of the area. Oslo city centre and the Bjørvika district itself are home to Oslo Central Train Station as well as the famous Oslo Opera House and the Barcode Project, a modern development of several high-rise buildings along the harbour front. A recent study estimated that the remedial costs for reparing all of the issues suffered in Oslo city

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[35] https://www.ha-halden.no/nyheter/jon-georg-dale/intercity/svart-darlige-grunnforhold-og-dyrt-a-bygge-i-by-derfor-ruller-milliardene-for-jernbanen-i-ostfold/s/5-59-1639099?fbclid=IwAR21AkI5IcXzMfUx7NoV1WsMh_2qIXcPe0RsO7a3aFc8k5_Z_CxnRuLrSdc

[36] https://issuu.com/ngu_/docs/suburban_magazin_pages

centre and the Bjørvika district as a result of the ground instability would reach €6 billion[36]. Using InSAR during the design phase along with thorough on-site investigations to locate problem areas can help engineers choose the safest drilling and piling areas, meaning they can avoid interfering with soil pressure and groundwater. This may bring with it larger up-front costs, as slower drilling and piling methods may have to be utilised, however it avoids costs at a later stage, like the €6 billion reparations required for Oslo city centre. In order to estimate some of the saving InSAR could bring to the design phase of construction works similar to the Oslo city centre/Bjørvika redevlopment, we will assume the following:

- We will conservatively estimate that 1% of the remedial construction costs could have been avoided had InSAR given the engineers a better understanding of the ground conditions at the design phase. This gives us a cost saving of €60 million. (In reality we believe InSAR would contribute a lot more to avoiding these kinds of issues, but in the interest of keeping things conservative, we will stick with 1%).
- To scale this to a yearly nation-wide cost saving figure is quite difficult, but some very conservative assumptions can be made. Given that the Oslo/Bjørvika development is a particularly large undertaking in the heart of the capital city, we cannot assume similar sized construction works would be consistently dotted throughout Norway on an ongoing basis. We can, however, conservatively assume that given Norway's size, known ground stability issues and other major cities and ports (Bergen, Stavanger, Trondheim, Tromsø, etc.) that across the entire country a saving of between 5% and 10% the size of the already conservative estimate for Oslo/Bjørvika could be made each year. **This gives us a nation-wide saving of between €3 million/year and €6 million/year on infrastructure developments similar to that in Oslo/Bjørvika that could be avoided if InSAR technology has been used.**

We have seen from three examples of projects; the Frodeåsen tunnel in Tønsberg, the Fredrikstad infrastructure development and the Oslo/Bjørvika development that there are economic savings to be made at the design phase of projects by using InSAR to detect areas of risk prior to construction. Taking the average of the benefits calculated from the Frodeåsen tunnel in Tønsberg (€166,666/year to €333,332/year), the Fredrikstad infrastructure development (€1.92 million/year to €3.84 million/year) and the Oslo/Bjørvika development (€3 million/year to €6 million/year) gives us an estimate of yearly cost savings in Norway of this kind of between €1.7 million/year to €3.4 million/year.

Another, more general benefit of using InSAR at the design phase of road infrastructure construction is the increase in lifespan of road surfacing. In general, the average lifespan of road surfacing is about 7 years, meaning every 7 years resurfacing must take place to keep the road in good condition and within the regulated safety limits. The use of InSAR across the entire country allows for better choice of road paths and better choice of building technology in difficult areas, which all contributes to an increase in surface lifespan. It has been estimated that the average lifespan will increase from 7 years to at least 8 years, or a 14% reduction in resurfacing requirements[37]. If we assume an an annual budget of €50 million for resurfacing the entire country's roads, a 14% reduction in this requirement equates to a saving of €7 million. We can conservatively assume that 10% - 20% of these savings could be attributed to the use of InSAR, implying a saving of between €700,000/year to €1.4 million/year. As this saving is on a much more macro level and is a constant every year across the entire road network of Norway, it will be counted separately to the "project" related savings calculated and averaged out across the Frodeåsen tunnel in Tønsberg, the Fredrikstad infrastructure development and the Oslo/Bjørvika development. Note also that this is a future benefit which will arise as more roads are built with less instability.

2 - Benefits at the operational phase: Determining risk and damage to current infrastructure

Improved monitoring and maintenance of roads can be achieved through the use of InSAR technology, once in their operational phase. Issues with underlying ground conditions that may arise throughout the road infrastructure's lifetime can be picked up on in their early stages, giving engineers more time to develop solutions to mitigate the problem. This reduces the chances of structural issues developing into something catastrophic, saving both money and resources on behalf of the road authorities. Not only can these issues be spotted in time, the fact that InSAR technology can cover an entire country every 5-6 days means that the full expanse of Norway's road network can be constantly monitored. This implies that the likelihood of issues being missed in remote or quieter parts of the road network, which generally would not be monitored very often, are no less likely to slip under the radar. All in all, this improved monitoring leads to road closure instances being reduced, saving money for the likes of the NPRA and reducing negative effects on road users' lives.

Given Norway's mountainous terrain, road closures in the country can also lead to particularly lengthy detours. In a lot of the remote locations on Norway's coast, around its fjords and amongst its interior mountain ranges, there is only one road connecting small towns and urban areas. If roads of this kind are forced to close, the options for road users to get to their desired location can be extremely long and inconvenient, or in some cases, non-existent. The volumes of traffic affected in these scenarios are not huge, but for the few road users that are affected, the impact on their lives can be significant. There are also safety concerns involved with road closures, given that landslides can often be the cause of these closures. Therefore, there is a public safety dimension to the widespread monitoring of road infrastructure in Norway. As the benefits associated with improved maintenance of the road network affect society as a whole to a large extent, the benefits will be quantified in Tier 4.

The Tier 2 benefits are summarised in the table below.

[37] Gjersum, Haakon (2018): Norsk nytteverdi av EUs romprogrammer (Norwegian usefulness of the EU space programmes), internal Norwegian Space Centre, not for public release, 174 pages.

Summary of Tier 2 benefits	€/year in Norway
Improved surveying reducing project costs	€30,000/year - €100,000/year
Detecting areas of risk at the planning phase of projects	€1.7 million/year - €3.4 million/year
Reduction in road resurfacing costs due to a better planned road nework	€700,000/year - €1.4 million/year
Improved maintenance – reduced risk of road closures	Counted under Tier 4

5.2.3 Tier 3: Construction and related industries

A number of actors, namely Multiconsult, Skanska, BaneNOR, and NGI, along with their roles in Tier 3 of the primary value chain, have already been described in Chapter 4 of this report. Although these actors all experience benefits as a result of the use of InSAR technology, the most concrete and quantifiable benefits we have identified at the pre-construction phase of a road infrastructure project are encapsulated in Multiconsult's monitoring of the pre-construction phase of a bridge at Sifjord. Therefore, the benefits experienced by Skanska, BaneNOR, and NGI will remain as qualitatively described benefits in Chapter 4 and will not be used for any bases of monetary calculations in this section.

To recap, the road running around the Sifjord had been subject to multiple rock falls and avalanches. In one tragic accident, a car was hit by a rock fall, and school buses were forced to pass the road twice each day, meaning local villagers were concerned for their children's safety. Hence, in this NPRA lead Troms and Finnmark County Council project, it was decided to build a bridge across the head of the fjord to avoid the need to drive past the dangerous stretch of road. It was also decided to construct a causeway using rocks deposited into the fjord. The rocks forming the ballast had to settle to within a tolerable limit before the construction work could start, with this settlement potentially taking between 9 and 12 months.

The use of InSAR in conjunction with strategically placed corner reflectors on the ballast rocks meant that changes in the elevation of the settling foundations could be tracked remotely with very high precision. Normally it would have required personnel to travel hours to and from the location to make measurements. During winter closed roads due to avalanches and bad weather complicates the logistics, and fewer measurements would have been taken using traditional field based techniques (e.g. levelling). The millimetre precision InSAR measurements were available at a relatively high temporal resolution (new measurements every 6 days, and new processing and reporting every 14 days), meaning the changes in the relative vertical movement of the bridge's foundations could be graphed automatically and analysed to give a picture of the constantly evolving settlement rate. The precise and constant monitoring of the foundation's structural integrity meant that the likelihood of premature construction work going ahead, which could lead to further issues and additional costs at a later time, was reduced. This technique allowed Multiconsult to monitor the motion and conclude that it had reduced inside the defined limit faster than would have been the case without the InSAR measurements with high temporal resolution.

Consequently, two forms of savings can be identified:

- Firstly, the project time saved by being able to start construction work earlier and with confidence.
- Secondly, the cost of surveying to provide the same result.

In order to provide an estimate of the saved project time, discussions were held with Multiconsult. Multiconsult themselves conducted an analysis of project savings as a result of using InSAR. This was then reviewed with the construction company concerned, which concluded that there were no savings in this specific case, for three reasons:

- There was an additional cost of installing the corner reflectors on the large concrete blocks, plus the subsequent removal of these blocks offset any savings.
- The company had ongoing work in nearby areas, meaning that surveyors were within the vicinity of the bridge anyway. This implied that the full costs of sending a surveyor using traditional means to survey the bridge alone were lower than usual.
- There was an investment cost into the manufacturing of the corner reflectors and the learnings associated with the use of InSAR.

However, it is considered that in different circumstances, for example, where construction was in a more remote and/or more hazardous area, there would be savings through the use of InSAR technology. Hence, we are using the Sifjord example to estimate the benefits and will then project these onto future projects.

Benefit from project time savings

- The bridge construction cost is roughly €5,000,000 and will take 12 months to complete. Therefore, the weekly cost is approximately €100,000. Most of the costs remain the same even if the start date of the works is the same, but there is an overhead to the project that will increase if it takes longer. We have taken 10% of the project costs as overhead (i.e., €500k or €10k per week) and will assume that the bridge works can start four weeks earlier through the use of the InSAR surveying technique.
- **We, therefore, arrive at a benefit of €40,000 to the project.**

To scale this up to an annual figure which covers the entire country, we will use the following assumption:

- As we had previously assumed in the other tiers of this value chain, Norway has a total of 20 road infrastructure projects per year. We will assume 5% of these projects could benefit in a similar fashion to the Sifjord project by using InSAR technology to help save time. That leaves us with one instance of such a project throughout Norway each year.
- **In total, this gives us a potential time saving cost, at the construction phase, of €40,000/year.**

Benefit from improved survey methods

- Using traditional methods, the accuracy of vertical measurements is considerably less than using InSAR. Even the use of GNSS will not give much improvement in measuring a vertical displacement. A local augmentation system will need to be set up to provide an equivalent measurement accuracy. In a similar fashion to the Tier 1 survey cost benefit, we will assume the cost of this system as €20,000.
- In addition, a surveyor will need to go to the site to make the measurements on a regular basis. We will assume ten visits are needed at the construction phase of each project, with each visit taking one day. Taking a surveyor cost as €500 per day gives a cost of €5,000. **This gives a total cost for "traditional" methods of surveying during the construction phase as (€20,000 + €5,000) = €25,000.**
- Again, we do not have accurate figures for the cost of the contract to provide regular InSAR measurements over a given site, but in discussion with several companies supplying this type of product, we estimate that this should be around €10,000-€15,000.
- **Therefore, we estimate that the economic benefit of using InSAR methods at the construction phase of an average project will be between €10,000 and €15,000** (€25,000 - €15,000 or - €10,000).

To scale this up to an annual figure which covers the entire country, we will use the following assumption:

- Taking the previously assumed 20 road infrastructure projects per year in Norway, we will assume 5% of these projects could benefit in a similar fashion to the Sifjord project by using InSAR technology to accurately survey and monitor construction work. That leaves us with one instance of such a project throughout Norway each year.
- **In total, this gives us a potential reduction in surveying costs, at the construction phase, of between €10,000/year and €15,000/year.**

The Tier 3 benefits are summarised in the table below.

Summary of Tier 3 benefits	€/year in Norway
Project time savings at construction phase	€40,000/year
Improved construction surveying methods	€10,000/year - €15,000/year

5.2.4 Tier 4: Citizens & Society

As previously discussed, the culmination of all efforts by the authorities behind the InSAR Norway service, the authorities responsible for the management and development of the road network, and the construction companies who build and maintain the network ultimately serve the citizens and society of Norway. InSAR technology has benefited and will continue to benefit society through the establishment of a better planned, built, and maintained road network. It must also be noted that as InSAR technology becomes more widely adopted, these benefits will only increase in the future. We have identified a number of ways in which the citizens and society of Norway benefit in this case:

1. Projects are brought to completion faster and with less additional costs
2. There is a reduced risk of road closures
3. Better roads ease traffic, helping the economy flourish, easing peoples' lives and reducing pollution

Each of these benefits will be discussed in more detail below.

Projects are brought to completion faster and with less additional costs

Through the use of InSAR, faster, more efficient, and better executed road infrastructure projects are being undertaken, meaning the likelihood of delays or additional costs being incurred is reduced. This implies that taxpayers' money is being used effectively, and road infrastructure projects are not becoming a drain on public finances. This, in itself, is a "win" for society as it can be shown that public funds are being used in as efficient a manner as possible. In quantifying this benefit, we can look to the previous tiers of this value chain for the monetary benefits of projects being planned and executed more efficiently. Therefore they will not be counted again at this stage. Demonstrating that public funds are being used more efficiently is, unfortunately, a more difficult benefit to quantify and will remain reported as an intangible but very real benefit for society in this report.

A second benefit to the efficient and swift completion of road infrastructure projects is the fact that the impact on peoples' lives is minimised. These projects, particularly the major ones, can bring with them road closures, lengthy detours, and general upheaval of the public's day to day business. This benefit will be quantified in the following section.

Reduced risk of road closures

As already discussed, using InSAR can help minimise the length of time for road closures as well as helping to avoid them completely. Road closures impact citizens' lives negatively by cutting off routes of travel and enforcing alternative detours, adding time to peoples' journeys, and generally disrupting daily routines or activities. There is also a societal cost associated with road closures due to the investment involved in building roads not being able to manifest a "return on investment" as a result of its closure. To quantify the cost to society of a road closure in monetary terms is a little difficult, but some conservative assumptions can be made:

- According to their publication in 2018, the annual NPRA budget is approximately 35 billion NOK (€3.5 billion).[38]

[38] Statens vegvesen, PPP June 2018: https://www.vegvesen.no/_attachment/2335939/binary/1264526?fast_title=PPP+Norway+June+2018.pdf

- If we assume a very conservative cost/benefit ratio of 2[39], the investment of €3.5 billion per annum made by the NPRA should deliver overall benefits of €7 billion.
- If this is amortized over 20 years, the benefit is €350 million per annum or €7 million per project (taking the previously assumed 50 projects per year into account).
- **This further breaks down to roughly €135,000 per project per week. We shall use this figure as representing the average societal cost for a road or highway being out of use for one week. This can be thought of as a "loss of benefit" cost.**
- We will also assume that the average length of time per road closure will be two weeks.

Given the difficulty in estimating the benefits in this tier of the value chain, minimum and maximum estimates have been provided. The table below shows the conservative "minimum" cost estimate, which uses the figures already discussed and a "maximum" cost estimate, which is still a conservative assumption but gives an upper limit to the possible cost estimates.

Parameter	Minimum	Maximum
Average societal cost of a road being out of use per week	€135,000	€135,000
Number of projects which involve road closures per year	5	7
Average duration of road closure	2 weeks	4 weeks
Total opportunity benefits due to reductions in road closures	**€1.35m/year**	**€3.78m/year**

Better roads ease traffic, helping the economy flourish, easing peoples' lives and reducing pollution

As already discussed in detail in section **4.2.4 - Tier 4: Road users, citizens, and society**, a well-planned and maintained road network, in any country, brings with it major socio-economic benefits. Having well connected cities, ports, and regions can help boost the economy of a country, as it reduces non-tariff barriers to trade. A well-developed road network encourages the easier and swifter transport of people, capital, and goods, thereby stimulating business and economic activity. Although these benefits are undoubtedly real and are experienced in Norway as a result of having an efficient road network, quantifying these benefits, and especially quantifying the contribution InSAR makes to these benefits is extremely difficult. Therefore, this benefit will remain reported only qualitatively in this case.

The Tier 4 benefits are summarised in the table below.

[39] The figure of 2 comes from the assumption that, in the long term, benefits are shared equally between 2 parties. In reality, public decisions are more usually based on higher ratios which would show greater benefits deriving from the use of InSAR Norway.

Summary of Tier 4 benefits	€/year in Norway
Faster completion of projects with less additional costs	**N/A** – Already accounted for under Tier 2 and Tier 3 benefits
Reduced risk of road closures	€1.35 million/year - €3.78 million/year
Better, more efficient road networks	**N/A** – Will remain reported as a qualitative benefit in this case

5.3 The Secondary Value-Chain

As noted in Chapter 4, we are taking the step to introduce a second value chain into the case. One of the origins of the ground motion service lie in the goal of detecting rock slides and potential tsunamis with sufficient warning to avoid casualties. As a result, we decided to look at this as a secondary value-chain, where we shall describe what is happening without fully analysing the economic benefits. Finally, we also discuss the benefits of the Norwegian Avalanche Warning Service.

5.3.1 Tier 1: NGU and partners

As in the primary value chain, both NGU and NORCE act as service providers once again in this value chain: NORCE providing technology and NGU providing data products. Similar to the benefits experienced in the primary value chain, the symbiotic relationship between NORCE and NGU has developed into a positive value-creation ecosystem. As NORCE is a not-for-profit organisation with a strong research focus, they are using any revenue to help develop further research. NORCE benefits from the knowledge gained from this experience, helping them to develop new products and services.

5.3.2 Tier 2: NGU

NGU is considered as the primary user in this value chain, despite the fact that they have helped develop and operate the InSAR Norway service.

The InSAR Norway data has dramatically improved NGU's ability to identify unstable mountain slopes. Within the first month after launch in 2018, over 100 new unstable slopes were identified. These are now being mapped in the field to assess their hazard and risk to society.

In addition, it has had a great impact on the long term, periodic measurement of slope motion. Prior to the use of the InSAR Norway map, NGU had to hire helicopters for a number of weeks every year and use them in conjunction with GPS technology to measure motion of unstable slopes. The use of helicopters and GPS technology historically involved large costs, coupled with the environmental impact of the helicopters burning fuel to undertake the flights. The use of helicopters also only provided a snapshot of ground motion, providing one measurement per year. Now, with the help of artificial corner reflectors mounted on these slopes, together with the InSAR Norway service, NGU's geologists can obtain measurements every two to three days throughout the year.

5.3.3 Tier 3: NVE

NVE benefit in this case as a direct result of NGU's more expansive and more accurate identification of potentially dangerous areas of ground subsidence. There is a much lower likelihood of NGU missing or incorrectly classifying an area of concern thanks to the use of the InSAR Norway service, meaning, NVE can keep on top of all potential rock slide events and implement mitigation measures earlier and with greater effect.

5.3.4 Tier 4: Citizens and Society

The obvious benefit for citizens and society, in this case, is the reduced risk of rock slides or tsunamis within fjords having catastrophic impacts on property and lives. As a result of the NORCE, NGU, and NVE working relationship, early warnings and mitigation measures relating to rock slides can be implemented earlier and with more effect.

With regards to secondary benefits to society in this value chain, the lower costs involved in using the InSAR Norway service ensures taxpayer's money is used more efficiently, while the reduced environmental impact of using InSAR technology is yet another benefit that can be felt at the societal level.

Earlier internal Norwegian socioeconomic analysis[40] before the InSAR Norway release has estimated an annual value of use of Sentinel-1 based InSAR in the national rock slide service of between 69 and 75 MNOK in the 2020-2030 period.

5.4 Additional applications – The Norwegian Avalanche Warning Service

Finally, the Norwegian Avalanche Warning Service brings with it a number of benefits for numerous stakeholders:

- NVE, the NPRA and the Norwegian Meteorological Institute (Meteorologisk Institutt) are able to fulfil their duties in monitoring for potential avalanches more accurately and with a lower cost thanks to the free and open data available from Sentinel-1.
- The NPRA can plan and mitigate for potential avalanches with greater effect, meaning road infrastructure design and planning is more effective, and road closures are handled more efficiently.
- Citizens and society benefit from increased public safety as a result of the efficient avalanche warning service implemented.

[40] Gjersum, Haakon (2018): Norsk nytteverdi av EUs romprogrammer (Norwegian usefulness of the EU space programmes), internal Norwegian Space Centre, not for public release, 174 pages.

5.5 Summary of Benefits

In this chapter, we draw together the different benefits to the stakeholders identified along the value chain, grouping them by six dimensions of the value-chain analysis.

5.5.1 Economic Benefits

Calculating the economic benefits associated with road management is more difficult than even some of the other applications! The nature of the work, i.e., large projects, sometimes with long durations, means that the benefits take some time to be recognised by the stakeholders in what are normally large, publicly owned bodies. In this case, and in a similar cases being addressed in Italy, the story becomes more significant than the accurate calculation of benefits.

Nevertheless, the economic benefits are very significant even if we are unable to provide a satisfactory calculation of them now; this will certainly change in a few years' time.

Table 5-1, below, shows the benefits calculated along the value chain for the use of the InSAR Norway ground motion service for roads management in Norway. As might be expected, the majority of the economic benefits fall in Tier 2 for the road's administration. This represents the capability offered by the ground motion service to have a better understanding of the underground conditions when the road is being designed and built, and hence the value of avoiding re-construction or redial works after the project has been completed.

The analysis shows a benefit of between €3.8 million and €8.7 million per annum for the task of road management in Norway. We consider this to be a conservative figure.

In the study, we have also considered that benefits can accrue in a second value chain based around the use of the ground motion map to monitor for rockslides. **Although it holds relatively small economic benefits in our analysis, the use of the InSAR Norway service (and InSAR technology in general) at the construction phase is seen to hold huge potential in the future.** Knowledge of ground motion can be used by architects, engineers, and planners to determine the best construction method for a given location. Moreover, construction companies can use the service to monitor the impact of their work, or the service can be called upon when dealing with any legal actions which may arise from construction work. These construction applications may require the use of higher spatial resolution measurements, but the use of the free service will allow for a first assessment as to whether this higher spatial resolution data is necessary.

Tier	Benefits identified	Annual economic value stemming from the use of Sentinel-enabled services and the InSAR-Norway map	
		Minimum	Maximum
Tier 1 (NORCE)	Symbiotic relationship between NGU and NORCE encouraging value creation.	**N/A**	**N/A**
Tier 2 (NPRA)	Improved surveying methods reducing project costs at design phase	**€30,000**	**€100,000**
	Detecting areas of risk at the planning phase	**€1,700,000**	**€3,400,000**
	Reduction in road resurfacing costs due to a better planned road nework	**€700,000**	**€1,400,000**
Tier 3 (Multiconsult)	Project time savings at construction phase.	**€10,000**	**€40,000**
	Improved surveying methods at construction phase.		
Tier 4 (Society)	Reduced road closures.	**€1,350,000**	**€3,780,000**
Totals		**€3,790,000**	**€8,720,000**

Table 5-1: Summary of Economic benefits by Tier.

5.5.2 Environmental

The environmental benefits from the use of the ground motion service for road network management are small to non-existent.

Roads are considered as having a high impact on the environment both through the loss of countryside and the possible impact on natural habitats. They can also lead to the increased use of motor vehicles and hence higher carbon emissions. To the extent that the InSAR maps may help deliver more efficient highway management, there could be considered a small consequential impact on the environment. Also, in the secondary value chain, the reduced use of helicopters for scouting potential landslides does bring with it a reduction in carbon-emissions. Nevertheless, the overall environmental benefit, in this case, is quite small.

5.5.3 Societal

Societal benefits are arising from a number of impacts. NGU has first developed this service as a means to improve the monitoring of rockslides especially those with a potential to cause a tsunami which, as in the past, are a risk to property and life. The use of the service is reducing this risk by providing more constant and precise measurements of mountainsides where rockslides may occur. The service today is being used more widely bringing further societal benefits through better and safer roads.

The service can then contribute to understanding better the causes of house subsidence hence reducing subsidence risk and finally benefits caused by knowing if specific areas are vulnerable to ground motion and hence avoiding construction projects completely. Whilst it can be argued that there is a liability risk to the service-provider, as a national service, there is considered to be a greater benefit coming from the knowledge of past subsidence. This will become even more important as a history is built over the whole of Norway. Many other services may benefit from this knowledge; ie. Developers, construction, property owners etc.

5.5.4 Regulatory impact

Regulatory impacts are those where the use of satellite-based technology can lead to better policy development and or implementation. As we have discovered during this case, there are a number of areas where knowledge of ground movement can lead to better regulation. Simply the ability to measure the movement and to track it over time allows both a better understanding of what may be causing the movement and when it is happening. As in a SeBS case in Spain[41], more precise and large-scale measurements can enable limits and conditions to be built into regulations which would otherwise not be possible.

A time series of ground motion data combined with other data can enable forecasts to be made. This can be critical for long term effects. Today, NPRA and contruction engineers are responsible for any damage they do to neighbouring buildings for a period of 5 years after the work has been completed. Many of the movements are of a scale of mm per year meaning that it can take many years before the movement is detected - 10 or even 20 years is common - before the impact is felt. Precise, large-scale measurements are almost impossible with other technologies but become possible with InSAR. Hence, the InSAR Norway service can lead to better regulation through the ability to detect and measure these longer term impacts.

Other regulations may also be improved through being able to measure and monitor movement of the ground. Examples cited to us are; harbours and coastal developments (there are significant movements visible in some harbours) where subsidence, added to sea-level rise, means that infrastructure will be in danger, building permissions where the knowledge of a site's vulnerability can prevent later problems, controls over drilling (for whatever reason) where the impact can be

[41] Aquifer management in Spain, SeBS case to be published.

monitored using the InSAR Norway service, and finally, for the developments of road infrastructure where the risk of potential impact on exisdting infrastructure may be subject to regulatory limits.

One of the roles of the NPRA is to advocate and recommend techniques, technologies and procedures to other bodies at regional level responsible for roads. The use of the InSAR Norway map will now be included in their regularly updated “handbooks” relating to planning and engineering guidelines for road construction in Norway. Although not a regulatory matter, these guidelines are largely followed.

5.5.5 Innovation & Entrepreneurship

InSAR as a technology is fairly new and advances are being made in the processing and the use of different data types. The potential for innovation in both the generation of the product as well as its use in different situations is very strong.

We see in this case how departments within the Norwegian administration start to become aware of InSAR Norway. We see in NPRA how it starts to be used for some projects but the potential for its wider use is very clear and sound. As ground motion maps find their way into the hands of more operational parts of organisations so the potential for new uses and innovative uses becomes highly likely.

InSAR Norway has lready started to create awareness and bring new potential users. InSAR Norway has attracted 3000-4000 users a month with many within new user segments ie. insurance, real estate, climate (sea level, strom floods, harbour development), urban development, municipalities, engineering and consultancy. InSAR Norway has very strong potential to drive innovative uses within these sectors.

The presence of NORCE within the team generating the maps provides a direct link to innovation and entrepreneurship. We also learned that local industry (e.g. Multiconsult, Kongsberg Satellite Services) is gaining access to highly skilled staff, trained in the use of the maps.

Hence the overall potential benefits for InSAR Norway to stimulate innovation and entrepreneurship is very strong.

5.5.6 Science and Technology advancement

Here, there are two aspects to consider. Firstly, are the advancements coming from the development of the product itself?

Yes. The InSAR Norway ground motion service has spawned improved algorithms for generating the InSAR measurements along with the computational side of improved data-handling, processing, storage, scaling and visualisation and other factors linked to the overall accuracy of the map and the efficiency with which it is generated.

More satellite SAR systems are being developed and so new and more efficient processing algorithms are highly likely to emerge.

Secondly, are contributions to scientific research being made from having a country-wide map of ground motion?

Yes. In discussion with John Dehls of NGU, we learned about the ongoing studies of large-scale rockslides, for which the map was first conceived. The map allows new studies and more frequent monitoring of risky areas, furthering geological understanding of how landslides occur and how to better predict them. In this way, the map is fulfilling its core purpose for an operational research topic.

Further applications will emerge and scientific research will almost certainly drive these.

5.5.7 Summary of Indicators Used

Here we provide a list of the indicators which have been used in the analysis of this case.

Benefit type	Indicators used
Economic	• Improved surveying reducing project costs (Reduced inputs) • Reduced risk to projects and communities (Reduced costs) • Improved maintenance – reduced risk of road closures (improved efficiency) • Project time savings (reduced costs) • Improved surveying methods (improved efficiency) • Reduced road closures (Improved efficiency)
Environmental	• None
Societal	• Increased public safety and lower risk.
Regulatory	• Improved design and application of regulations and guidelines • Improved monitoring of regulations
Entrepreneurship & Innovation	• Development of new, Innovative products • Opening of new market opportunities
Scientific and Technological	• Enhanced scientific and technological knowledge

Table 5-2: Indicators used in the case

6 Key Findings and Final Thoughts

6.1 Key Findings

The Norwegian ground motion service, InSAR Norway, has been introduced by NGU, Norwegian Space Agency and NVE in Norway to support mapping of rock slide risk and subsidence of infrastructure. As a publicly funded service, the map is available to anyone in Norway on a free and open basis and, in one example, has been used by the NPRA to help manage the construction and maintenance of the road network.

In this case, the following aspects stand out:

- Future economic benefits to the road sector in Norway coming from the use of the ground motion map service are estimated to be between €3.8m and €8.7m per annum. These figures are considered to be very conservative and a more detailed analysis using better information on project costs would surely lead to higher numbers.
- The road infrastructure sector is driven by projects meaning that at present, it is a little early to assess the benefits due to the limited number of examples which can be taken. Road projects have a long lifetime with several years in planning and construction before a multi-decade period of use. Nevertheless, each project provides a story from which the impact of the use of Sentinel-derived information becomes clear.
- Construction projects, whether for roads, railways, or buildings, can benefit from a better and larger overview of ground motion and ground conditions in order to achieve the best possible foundation system. The use of InSAR Norway to find underlying instability over large areas is a unique service. Further, the large-scale, large-area nature of satellite observations and the high-precision vertical measurements are unique capabilities. InSAR Norway gives a quick overview of underlying soil conditions in early stages of projects and provides an ideal starting point for further ground investigations. During and after construction of infrastructure the satellite data continues to be valuable.
- During concept studies and early regulation phases for new road connections, reflectors can be installed in areas with potential for future road construction. The concept study and early regulation phases often take a long time. This means that there will be time to do useful InSAR measurements related to corner reflectors that can be used in the early design phase and planning of ground condition investigations.
- InSAR will also be valuable for future turnkey and functional requirements of road construction in Norway. Here, the entrepreneurs will have the main responsibility for the road construction, while the builder will control the functional requirements afterwards. Use of satellite data and InSAR for monitoring and possible maintenance commissioning can be clarified and agreed between builder and entrepreneur.
- As the time series of measurements gets longer, the ability to track and measure ground movements will get even better. A lot of the value of the InSAR Norway service lies in the future.

- There are a number of alternative uses for the Norwegian ground motion service; indeed, the original motivation for its introduction was coming from the potentially severe risk of rockslides and subsidence of infrastructure. More applications are likely to emerge as the unique value is more widely known.
- An alternative product using Sentinel data to detect where avalanches have occurred is also used by the roads administration (NPRA).
- In addition to the economic benefits, many other dimensions of value will also benefit from the use of InSAR Norway; societal, regulatory and innovation dimensions especially.

This is a project-based sector, which means that the analysis of benefits is harder than for other situations. We have identified and chosen 4 projects on which we are able to construct the story and the analysis. The 4 cases are quite diverse dealing with different situations and as such, are quite complementary:

- The example of the Frodeåsen tunnel in Tønsberg shows how the capability of Sentinel-1 synthetic aperture radar is uniquely able to identify large-scale problems. Engineers and surveyors looked at the conditions around the tunnel itself – without finding a conclusive reason for the subsidence. The Norwegian ground motion service showed that the whole town is located on unstable geology. It is inconceivable that traditional surveying would have identified this problem.
- The building of a new road and railway line in Fredrikstad has encountered severe subsidence problems attributed to the underlying geology where piling has pierced layers of clay. The extent of the problem renders traditional surveying very expensive, and the use of InSAR Norway is proving valuable to finding a solution.
- Using Sentinel-1 data with corner reflectors and InSAR measurements with high temporal resolution have given better foundation for decisions made during the pre-construction phase of a new bridge in Sifjord.
- Finally, in Oslo, the Bjørvika area is being redeveloped around the railway station, an area of known subsidence. The use of the Sentinel-1 data for InSAR measurements is able to highlight the more vulnerable points and inform corrective engineering works.

Each of these provides a guide for how ground motion services can be used more widely in the future. Even today, the economic benefit is high. Our analysis shows that a benefit of around €3.1 to €7.3m can be expected each year coming from road building activities for the Norwegian citizens and society. These numbers are of course higher when considering all uses of the service. Internal analysis by the Norwegian Space Agency and NGU are predicting a value of €9.7m for roads, around €7m for rockslides and a further €1m for avalanches (Sentinel data but not InSAR).

InSAR Norway is also critical to the NVE and NGU to support their work to identify and monitor unstable mountainsides. Severe rockfalls in the past have led to tsunamis, which flood coastal and lake settlements and even lead to loss of life. We have not tried to place an economic value on this activity, but clearly, InSAR has an important role to play. Earlier internal Norwegian socioeconomic analysis[42] before the InSAR Norway release has estimated an annual value of use of Sentinel-1 based InSAR in the national rock slide service of between 69 and 75 MNOK in the 2020-2030 period. These calculations need to be recalculated in light of new more exact knowledge on the socioeconomic effects after the InSAR Norway release. This is beyond the scope of this report. The use of corner reflectors to enhance the radar signal enables very precise measurements to be taken and detect if the rock is moving. A steady motion may not be a problem, but any acceleration could be an indicator of catastrophe. The InSAR Norway maps are not used as an alarm, but it can be a trigger to investigate further and to take precautionary steps if necessary.

In summary, the subjective assessment of the degree of the benefit contribution for each of the benefit dimensions is shown below in Table 6-1.

Economic	Environ mental	Societal	Regulatory	Innovation & Entrepreneurship	Scientific & Technological
★★★★		★★	★★★★	★★★★	★★

Table 6-1: Benefits Assessment by Category

6.2 The Impact of Sentinel Data

In most of the SeBS cases that we have looked at, the benefit of the service has been calculated, and we then have to determine how much of this can be attributed to the use of the Sentinel data. In the case of the Norwegian ground motion service, we have identified examples where there is no question that all the benefit is attributable. This is because there is no real practical alternative to gathering the information.

Sentinel data is fundamental to delivering these benefits. Ground motion maps in Norway are from 2018 generated entirely using Sentinel-1 data and is 100% dependent on it. Hence there is no question of attribution. At the next level, even if the ground motion map is one input among many used by planners, surveyors, and engineers to develop and maintain the road network, we have seen in the examples that no other source can provide information which is comparable whether in turns of scale or of precision.

While the nationwide ground motion map is currently generated only once per year, over designated areas, the data is available to generate local maps more regularly; weekly if necessary. Individual networks of corner reflectors can be measured every two to three days. Hence, the maps can be used for timely monitoring of any displacements, as we have described for the example in Sifjord.

42 : Gjersum, Haakon (2018): Norsk nytteverdi av EUs romprogrammer (Norwegian usefulness of the EU space programmes), internal Norwegian Space Centre, not for public release, 174 pages.

In terms of ground resolution, where specific points need to be measured, corner reflectors are deployed to give an enhanced signal. This dominates the radar return and hence can be localised to the exact position of the corner reflector.

6.3 Widening the Perspective

The case has analysed the use of the InSAR Norway, ground motion map as a tool for managing the country's road system. How may this be developed over a wider perspective?

Geographical Extension:

The geological structure of Norway means that there are many areas of the country where there is ground motion over a large area. Ancient glacial moraines have been built upon, and layers of clay exist that may move with time. These geological features follow the valleys and costlines of Norway where most of the population live and where the transport infastructure passes.

Our analysis considers the whole of Norway in terms of roads management. This and the case in Italy, show the strong potential for ground motion monitoring as a key tool for roads. Displacement and subsidence at the ground surface are not easy to detect – and is almost impossible with traditional surveying techniques. Mostly, the problems show up after construction has started, and the infrastructure is in place, which means costly repairs to the damage. Furthermore, most of the roads and railways are running along valleys where the settlements have been built. These are the very areas where the marine level has influenced the underlying geology and leads to areas at risk.

Other countries may not have the same geological conditions as Norway – which is somewhat unique. But many have different underlying geologies which can lead to ground motion; examples are the sands in the Netherlands, seismic activity in Italy and now moraines in Norway. We shall surely find others. Clay sub-soils are highly susceptible to changes in water levels, and water abstraction can lead to subsidence. Many more cases will be found, and InSAR technology has a wide application and a bright future market.

The range of economic benefits discovered in Norway, if extrapolated across the whole of Europe, would suggest a European-wide value of several hundreds of million Euro. The strong social and regulatory benefits can also be expected to be transferable to other countries.

A Europe-wide ground motion map will help to accelerate this development.

Increased Market Penetration:

Whilst applications similar to those we have analysed elsewhere (aquifers in spain, gas pipelines in the Netherlands) which stem from different geological problems, are probably not relevant for Norway, InSAR Norway will also be used for other purposes and not just for managing road infrastructure. We have described how the main, original goal for InSAR in Norway was as a tool to help identify and monitor areas of potential rockslides. We have also described how construction companies may be able to use InSAR Norway as a tool to monitor their works. In a sister case to this, in Italy, we have identified a situation where construction works were causing subsidence. A history of litigation built up between the Italian road authority and the engineering contractor, with regard to the cause of the subsidence. The use of an InSAR product helped lead to an investigation into the true cause of the problem. This applies to other construction works and not just to roads.

Hence, further uses by other sectors looks likely to increase the potential market for this tool. An annual, country-wide ground motion map for Norway looks to offer enormous potential to the country with a direct economic benefit many times the investment that has been made in the satellites as part of the EU Copernicus programme.

Increased Technological Maturity:

In other cases, we can see that data accumulated over time will add to the value of the Seentinel data. In the case of farming, the history of crop growth in fields will greatly add to the value of the service. In the case of InSAR a similar effect is anticipated where several yeasr of data showing the ground motion will enable a much better picture to be developed of the land characteristics.

Archives of SAR data now being built up, allow the history of a site to be looked at. InSAR Norway will take this one step further with a systematic survey of the whole country each year. Inspection of this database will allow problems to be identified and lead to further investigation. This will, in turn, provide better information on the geological conditions and enable the planners, architects and engineers to adapt the construction to the conditions.

The value of the service is likely to increase with time.

6.4 Final Thoughts

InSAR is at the same time a relatively mature technique but one which has enormous potential to be developed further. The full range of applications are only being discovered and many new potential users are yet to become aware of what can be achieved.

Our case is focused on its use for the management of the roads system in Norway. This decision was taken to enable some comparisons to be made between the use in Norway and in Italy. This starts to show the value of the SeBS value-chain approach as contrasts can be made between the two. For example, despite different governance systems, the benefits in the two countries both apply mainly to the roads authority and to society at large (tier 2 and tier 4).

The case has demonstrated clearly the strong benefits coming from InSAR technology and the potential economic benefits are very high. Furthermore, benefits are strong in other ways as well notably for societal factors and contributing to better regulation and control of infrastructure development. It would be an interesting exercise to look more closely at the impact of the regulatory systems and drawing such a comparison between different countries. Is there a European dimension as well?

Our analysis has dug into some examples of the early use of the new InSAR Norway ground motion service. Our approach based on story-telling backed up by detailed analysis based around assumptions is a highly effective and highly-appreciated method to start to calculate the benefits. Nevertheless, as the use of the satellite data becomes more common-place and as the understanding of its impact becomes more understood, further analyses can yield more insights and even stronger justification for the introduction of new services. A study of the benefits at a Euroepan scale which takes into consideration the different conditions in each of the Member States; geological conditions but also the management systems and the impact which this has.

We believe that our work is just starting to scratch the surface and we hope that we or others may be able to continue it to generate more arguments for investments in satellite systems as well as investment in the uptake and application for the benefit of citizens and society at large.

Annex 1: References and Sources

The list below covers only the main sources used throughout the study which are not directly available on-line. The reader can find more references in the form of footnotes or hyperlinks throughout the text. Numbers refer to the documents in the specific manual and, in brackets, the footnote number.

1. (1) "Here the houses are sinking"; Internal note translation of NRK article
2. (3) Facts about Road Transport in Norway
3. (8) COST sub-urban report; Case study on Oslo.
4. (14) NPRA report on Frodeasen tunnel
5. (19) Remote sensing of landslide motions
6. (25) JPL analysis of Genoa (Morandi) bridge collapse.
7. (24) Potential for using InSAR to measure bridge deformations
8. (31) The socio-economic benefits of roads in Europe
9. (34) Cost-benefit analysis for methods of ground deformation measurement
10. (35) Fredrikstad news article (Norwegian)
11. (38) PPP Norway
12. (26) Space for smarter infrastructure
13. (14) Fodeasen tunnel
14. (29) Subsidence monitoring of fjord crossing (Multiconsult)
15. (15) Report 2013-2017 Oslo Underground
16. (4) NGU: Geology in Norway: Link
17. (5) NGU: Quick clay in Norway: Link
18. (6) NGU: Quick clay accidents in Norway: Link
19. (7) NGU: Ground water in Norway: Link
20. (9) Pathways & Pitfalls to better Sub-Urban planning (2018): Link

Annex 2: Glossary of Abbreviations

GMES – Global Monitoring for Environment and Security

InSAR – Interferometric SAR

MTI – Multi-Temporal Interferometry

NGI – Norwegian Geotechnical Institute

NGU – Geological Survey of Norway

NOK – Norwegian Krone

NPRA – Norwegian Public Roads Administration

NVE – Norwegian Water Resources and Energy Directorate

SAR – Synthetic Aperture Radar

SeBS – Sentinel Benefits Studies

Annex 3: General Approach and Methodology

This case has been analysed as a part of the Sentinel Benefits Study (SeBS), which looks at the value being created by the use of Sentinel data. It follows a methodology[43], established during a previous study, looking at a value chain for the use of a single EO service.

For each case, a value chain is established with a service provider and a primary user. The value-chain is validated with these two key players. Through a combination of desk and field research, we develop our understanding of all the actors in the value chain, the role that they play and how they may benefit through the use of the satellite-derived products.

The value-chain is divided into a number of tiers where the supplier is Tier 1, and the primary user is Tier 2. The last Tier is always “Citizens and Society”. The number may vary according to the complexity of the value-chain. The benefits are then analysed against each of these tiers.

Once written, the draft report is then shared with all the persons with whom we have spoken, and their comments are incorporated, or a further discussion is held to establish a common understanding. Note that we are not asking these experts to endorse our findings but to indicate any gross errors or sensitivities which may have been introduced. At the end of this process, the report is made public.

As work has proceeded and more cases analysed, some modifications have been made to the methodology described in reference 43. The first of these has been to expand from the two dimensions used earlier, namely economic and environmental benefits, to add those connected to societal, regulatory, innovation and entrepreneurship and scientific and technological. These six dimensions are described in the table A2-1 below.

Dimension	Definition
ECONOMIC	Impacts related to the production of goods or services, or impacts on monetary flow or volume, such as revenue, profit, capital and (indirectly, through turnover generation) employment.
ENVIRONMENTAL	Impacts related to the state and health of the environment, particularly as regards the ecosystem services on which human societies depend.
SOCIETAL	Impacts related to societal aspects such as increased trust in authorities, better public health or secured geostrategic position.
REGULATORY	Impacts linked to the development, enactment or enforcement of regulations, directives and other legal instruments by policymakers.
INNOVATION-ENTREPRENEURSHIP	Impacts linked to the development of new enterprise and/or the introduction of technological innovation into the market.
SCIENCE-TECHNOLOGY	Impacts linked to academic, scientific or technological research and development, the advancement of the state of knowledge in a particular domain.

Table A2-1: Definitions for the benefit dimensions

[43] SeBS Methodology; June 2017.

For each of these, a ranking has been introduced to give an immediate, visual impression of the scale of the benefits under each dimension. To aid in the quantification of these, a guide has been introduced which is shown in Table A2-2.

Rank	Benefit status	Criteria
0	**Null**	The case presents no perceivable benefits in this dimension, and no potential for such benefits to emerge is anticipated.
1	**Latent**	The value chain described in the case may, in general, present potential benefits in this dimension, but none have been identified or described in this particular instance.
2	**Manifest**: At least one benefit in this dimension has been identified through the value chain within the case. Its significance in the context of the case overall is judged to be:	**Low**
3		**Moderate**
4		**High**
5		**Exceptional**

Table A2-2: The ranking of the benefits.

In order to introduce further basis for comparison, a systematic approach has been developed for the analysis of the benefits. A series of indicators have been defined for each of the benefit dimensions against which each case can be considered.

The indicators used in the case are listed in section 5.5, and a full list of all indicators considered is provided in Table A2-3.

Dimension	Indicator	What it can mean.
Economic	Avoided costs (AV)	Alternative means to gather data
	Increased Revenues (IR)	Increased production/sales
	Reduced Inputs (RI)	Less time spent or material saved
	Improved Efficiency (IE)	Better use of resources
Environmental	Reduced pollution (RP)	Reduced amounts of pollutants in key resources e.g. water, air
	Reduced impact on natural resources (RR)	Reduced environmental impact e.g erosion, habitats/biodiversity.
Societal	Improved public health (IPH)	Less toxicological risk
	Common Understanding (CU)	Better control and communication of remedial efforts i.e through common maps.
	Increased trust and better transparency (ITT)	Improved preparedness / response
	Strategic Value (SV)	Common societal value to a country or region.
Regulatory	Improved policy / regulation design/drafting	Better information (scale, accuracy) leading to better regulation
	Improved efficiency in policy/regulation monitoring	Better information available to monitor adherence to regulations.
Innovation & Entrepreneurship	Innovative products	Sentinel data leads to creation of new products / services
	New Business models	New ways to generate income.
	New markets	Global nature of sentinel data enables international business development
	New businesses	Creation of new companies; start-ups
Science & technology	Academic output	
	Research exploitation	Applied science to operational services
	Research contribution	New product enabling scientific research

Table A2-3: Complete list of indicators considered within SeBS analyses.

Annex 4: Winners… and losers?

The creation and subsequent usage of Sentinel data down the value chain has a significant economic impact. Quite prominently, product and process innovation based on the availability and subsequent application of the data, lead to positive effects where new products and services emerge, and existing processes can be run more effectively and efficiently. Conversely, of course, there are also consequences on some of the previous beneficiaries. For instance, revenues might be shifted, and jobs displaced and sometimes even destroyed, creating technological unemployment

> As we have shown in our study 'Winter navigation in the Baltics' as the captains on the icebreakers in the Baltics could suddenly rely on Sentinel based ice charts providing a fully synoptic picture of the ice, the helicopter pilots they traditionally relied upon, became abundant.[44] Similarly, in our study 'Forest Management in Sweden' the Swedish Forest Agency could reduce the number of forest inspectors, as Sentinel data allowed for a reduction of in situ inspections.[45]

How technological progress and innovation are related to employment has been an area of fierce debate for centuries. Fairly recent studies appear to show that product innovation sparks new economic activities, creating new sectors, more jobs, whereas process innovation[46] is more job destroying, although market mechanisms can sometimes largely compensate for the direct job losses, mitigating the ultimate impact on demand for labour. Such price and income compensations can derive from a decrease in wages, leading to an increase in demand for labour or the effects of new investments (enabled by accumulated savings) creating new jobs elsewhere. Obviously, the speed and impact of such effects are highly dependent on the flexibility of markets, the level of competition, demand elasticity, the extent of substitutability between capital and labour and, of course, possible institutional rigidity.[47]

> A German study on the co-evolution of R&D expenditures, patents, and employment in four manufacturing sectors concluded that patents and employment are positively and significantly correlated in two high-tech sectors (medical and optical equipment and electrics and electronics) but not in the other two more traditional sectors (chemicals and transport equipment).[48] Similarly, a study using a panel database covering 677 European manufacturing and service firms over 19 years (1990–2008) detected a positive and significant employment impact of R&D expenditures only in

[44] Sawyer, G. and De Vries, M. "Winter navigation in the Baltics." Copernicus Sentinels' Products Economic Value: A Case Study (2015)
[45] Sawyer, G. and De Vries, M. "Forest Management in Sweden." Copernicus Sentinels' Products Economic Value: A Case Study (2016)
[46] As process innovation is defined as producing the same amount of output with less labour (and sometimes other) inputs, logically the direct impact of process innovation is job destruction when output is fixed.
[47] Vivarelli, M. "Innovation and employment: Technological unemployment is not inevitable—some innovation creates jobs, and some job destruction can be avoided." IZA World of Labor 2015: 154

[48] Buerger, M., T. Broekel, and A. Coad. "Regional dynamics of innovation: Investigating the coevolution of patents, research and development (R&D), and employment." Regional Studies 46:5 (2012): 565–582.

> services and high-tech manufacturing but not in the more traditional manufacturing sectors.[49] Another study found a small but significant positive link between a firm's gross investment in innovation and its employment based on longitudinal data set of 575 Italian manufacturing firms over 1992–1997.[50]

Clearly, this tells us that the ultimate 'net' impact of innovation – both at product and process level - brought about by the availability of new technology, such as Sentinel data, will be closely related to the market and institutional settings in which they become effective. However, on the whole, the conclusion seems justified that the 'negative' effects, in the form of possible loss of employment, are largely outweighed by the positive economic effects throughout the value chain.

Accordingly, in this study – and likewise for the past and future ones - we will concentrate on the positive effects brought about by the availability of the Sentinel data throughout the value chain. That there are also (temporary) 'negative' impacts is a given, but the net effect at a macro level will always be positive.

[49] Bogliacino, F., M. Piva, and M. Vivarelli. "R&D and employment: An application of the LSDVC estimator using European data." Economics Letters 116:1 (2012): 56–59.

[50] Vivarelli, M. "Innovation, employment, and skills in advanced and developing countries: A survey of the economic literature." Journal of Economic Issues 48:1 (2014): 123–154 as well as "Technology, employment, and skills: An interpretative framework." Eurasian Business Review 3:1 (2013): 66–89.

Annex 5: About the Authors

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The SeBS study is conducted by a team of experts under the direction of ESA (the European Space Agency) and led by EARSC (the European Association of Remote Sensing Companies. The team is of a variable geometry and different experts work together on the different cases. The full team and the organisations for whom they work, is shown below.

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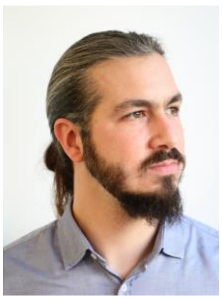

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