PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
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SUBAQUEOUS SLOPE FAILURES IN NORWEGIAN FJORDS

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Slides occur intermittently in subaqueous slopes in sand and silt which with respect to dimensions are unprecedented by slides occurring above the ocean level. These slides have been surrounded by considerable mystery as they frequently occur in slopes which, according to a conventional stability analysis, should be stable beyond any doubt, and in addition the extent of the failures observed above water along the shore line is in general very small compared with the volume of the slides in the submarine slopes. As these slides occur below water our knowledge about their nature and development is very limited. A description of such slides can be found in papers by Casagrande (1936), Barentsen and Lunde (1943 and 1946), Koppejan et al. (1948), Skaven Haug (1955), Terzaghi (1956), Watanabe (1965) and Andresen and Bjerrum (1967). Several theories have been put forward in order to give a scientific explanation of their development, see for instance Heezen and Ewing (1952), Kuenen (1952), Terzaghi (1956) and Andresen and Bjerrum (1967).

Slides of this type also occur in Norway from time to time, and in fact the majority have taken place in the fjords within a comparatively small area in the middle of Norway. They have all occurred in the postglacial deltas and estuaries which have accumulated where the rivers from the nearby mountains debouch into the fjord.

The data from six slides of this type have been collected, and a short description will be presented here. The location of the slides are shown on the map on Fig. 1. Subsequently an explanation is proposed which emerges from a study of these and similar slides occurring in other countries.

THE SLIDE IN ORKDALSFJORD, MAY 2, 1930

The slide in Orkdalsfjord (Fig. 2) is of special interest, because of some observations which permit an evaluation of its size and mode of occurrence. The slide took place on May 2, 1930. The fjord is 25 to 30 km long, and a maximum of 500 to 600 m in depth. Its bottom is built up of loose fine sand, silt and silty clay deposited by the River Orkla, and has a slope of 5 to 10 percent in the first five kilometers from the river mouth. Further out in the fjord the inclination of the bottom is only a few percent.

The slide occurred in the early morning at an exceptionally low tide and was observed at the following points (Fig. 2):

(1) At Storaunet about 1000 to 1500 m^3 of a minor filling which had been recently placed along the shore disappeared at 7:48 a.m. in a slide (slide A) that stretched 500 m along the edge of the fjord; it was preceded by the formation of a small wave some distance out in the fjord.

(2) A few minutes later a 600 to 700 m long slide at Orkanger, approximately 2 km away, destroyed some piers and harbour works, slide B.

(3) On the opposite side of the fjord a slide took place at Furenstranden at 7:55 to 8:00 a.m., slide C.

(4) Three kilometers from Storaunet the Ofstad-Sandløkken telephone cable crossed the fjord at a water depth of a maximum of 300 to 350 m. At 7:55 a.m. the cable was broken, indicating that the slide had propagated from Storaunet with a speed of about 25 km/hour.

(5) Approximately 18 km further along the fjord, the Vorpenesset-Stadsbygden cable crossed at a water depth of 500 m. Failure of this cable at 9:40 a.m. corresponded to an average speed of propagation of 10 km/hour since the occurrence of the initial slide.

From the observed changes in water depth it has been calculated that about 25 million m^3 of soil had been moved by the three first-mentioned slides (Vogt, 1943). Borings carried out near the areas where the two major slides A and B occurred indicate the existence of large deposits of a very loose and soft non plastic silt, having a water content of about 33 percent, corresponding to a porosity of about 49 percent.

THE SLIDE IN TRONDHEIM, APRIL 23, 1888

That part of the city of Trondheim which faces the sea and includes the harbour has been developed on the estuary of the river Nidelven. The estuary is built up of thick deposits of fine sand and coarse silt with occasional layers of clay. The sediments are postglacial and normally consolidated and therefore loosely deposited.

The harbour was originally a river harbour but since the end of last century its character has changed. The river outlet has been regulated, see Fig. 3, and new quays and piers have been built along the shore line by reclaiming areas by filling. During this period of development two large slides have occurred causing failures of harbour structures.

The largest of the two slides occurred on April 23, 1888. From the testimony of the witnesses (Skaven Haug, 1955) it has been established that the events started by the appearance of a 5 to 7 m high flood wave formed in the fjord about halfway between the island Munkholmen and Ilsvika, see Fig. 3. The wave propagated towards the shore line and first struck land at Ilsvika. Some minutes later it reached the jetty confining the area reclaimed several years earlier for the railway station at Brattøra. At the instant the wave reached Brattøra, or perhaps when it receded, the jetty and the fill behind it slid out with three railway tracks over a length of about 170 m. One man lost his life.

The jetty and the fill rested on the original sand surface sloping at 8-15 degrees towards the fjord. After the slide the depth of water next to the failed area had increased by nearly 10 m and as far out as soundings were made the increase in depth was of the same order of magnitude. The width of the slide next to Brattøra was about 600 m.

In the hours following the main slide some minor failures took place. Further east the jetty failed over a length of about 30 m in such a secondary slide. The slide occurred at low tide.

THE SLIDE IN THE HARBOUR OF TRONDHEIM, OCTOBER 8, 1950

On October 8, 1950, another large slide occurred in the harbour of Trondheim, but this time at Ilsvika, see Fig. 3 (Skaven Haug, 1955). In 1949 the State Railways extended their area by reclaiming a strip of land along the water front at Ilsvika. In 1950 another strip of land further out was constructed by the placing of fill on the natural bottom of the fjord, and by October 8 the construction was almost completed.

The slide occurred in the night and no details of the events are available. The visible result was the disappearance of the recently reclaimed area over a length of 150 m and with an average width corresponding to three railway tracks, see Fig. 3. From soundings carried out after the slide it was established that a very large area of the bottom of the fjord outside Ilsvika had been involved in the slide. The dimensions of this slide were of the same order of magnitude as those of the slide which occurred in 1888, in width being about 600 m and this slide also extended towards the middle of the fjord as far as soundings were made.

The soil conditions in the areas which were involved in the slide are known to be characterized by thick deposits of fine sand and silt. It is, however, notorious that below the recently placed fill outside Ilsvika some soft clay layers were present locally and it is though possible that the failure of the reclaimed railway area may be the result of an overloading of the clay with the fill which was up to 12 m thick.

THE SLIDE IN HOMMELVIKA, APRIL 14, 1942

The slide in Hommelvika in 1942 took place during the German occupation and as some military construction was involved no official investigation was permitted. The information presented here is collected from files of the Norwegian State Railways.

In the period up to the slide rock fill was being placed in order to reclaim an area in the harbour of Hommelvika for a military slipway for hydroplanes. Two days before the slide the outermost part of the fill slid out but the filling was resumed and continued until the main slide occurred, see Fig. 4.

The slide took place at 7:45 p.m. on April 14, 1942. This was 40 minutes after spring low water tide. The slide started by the disappearance of the area recently filled-in. It propagated quickly in a southern direction, see Fig. 4, and caused first the failure of another recently reclaimed area next to the Halstad river and then the failure of the outermost part of the deep water harbour recently completed by the Norwegian State Railways. Finally, the older part of the deep water harbour slid out.

Measured along the shore line the slide has a length of 450 m and on the average the slide came to a halt at a distance of about 40 m from the water front. Two men lost their lives.

From borings carried out in connection with the construction at the harbour for the State Railways it is known that the soil conditions in the area were characterized by thick deposits of fine grained and loosely deposited sand, with some clay just above rock.

SLIDE IN FOLLAFJORDEN, JANUARY 9, 1952

In the evening of January 9, 1952, a slide took place in the Follafjord about 190 km north-northeast of Trondheim. This slide is of some interest to study as a dredger was anchored within the area of sliding and its movements were carefully observed.

The situation before the slide took place is shown on Fig. 5. Follafjorden is a fjord about 600 m wide and 40 km long cut down between steep rock walls. The site of the events, Kongsmo, is a small village located at the extreme end of the fjord where an adjoining river has formed an estuary. From the estuary the bottom of the fjord slopes outward with an inclination of about 5 to 7%. The sediments are fine sand and silt and are known to be loosely deposited.

In the period preceding the slide a local mining company was constructing a small harbour. A dredger, "Yankee", was working at the location of the harbour shown in the upper left corner of Fig. 5. In the evening of January 9 it had been anchored by three 60-100 m long chains, nos. 1, 2 and 3, attached to anchors dropped at the bottom of the fjord, and by two cables, nos. 4 and 5, to the shore. At 8:03 in the evening anchor no. 3 was taken by a slide and broken leading to an outwards movement of the dredger and the failure of cable no. 5. During these events the sea was calm, but subsequently a 1-2 m high wave swept past the dredger.

After the sea had calmed down, the dredger was suddenly subjected to a powerful drag by anchor chain no. 2. The result was that the two remaining anchors snapped and the dredger was pulled by chain no. 2 over a distance of about 300 m from its original position to the place shown in Fig. 5. The velocity at which the moving anchor pulled the dredger was estimated to be about 15 km per hour. When the dredger stopped the time was 8:17, i.e. 14 minutes after the first slide.

It was later discovered that in the period between the first slide and the displacement of the dredger a tremendous slide had occurred in the interior part of the fjord, where the depth of water had increased by up to 20 m. Through the clear water the slide scar could be followed over a length of a kilometer, see Fig. 5. A consequence of this slide was the failure of two landing piers.

Borings located near the ferry boat landing pier shortly after the slide showed loosely deposited fine sands and silts to great depths. It may also be of interest to mention that after the slide several attempts were made to recover anchor no. 2 by which the dredger had been dragged out into the fjord. All attempts were in vain and finally the anchor chain broke.

THE SLIDE IN FINNVIKA, AUGUST 31, 1940

As a part of the construction of the railway line from Mosjøen to Bodø in 1940 a 4 m high and about 500 m long embankment was built to cross the small bay of Røyten at the northern shoreline of Finnvika Fjord about 3 km north of Mosjøen. The embankment was nearly completed when on August 31st at 7 o'clock in the morning, coinciding with a low spring tide, 100 m of the embankment disappeared in a slide, see Fig. 6. Eye-witnesses report that the slide had the appearance of a vertical subsidence.

About 5 minutes later the sediments forming the bottom of the interior part of the fjord of Finnvika were involved in a tremendous subaqueous slide (see Fig. 6) and disappeared together with a landing pier and a small commercial harbour. The slide caused an impressive wave which, a couple of minutes later, was observed to pass the site of the failure of the railway embankment.

In the days following the slide eddies and floating seaweed were observed repeatedly, indicating that the main slide was followed by secondary slide activity. These occurrences extended over a distance of at least 5 km, thus indicating tremendous dimensions for the slide.

Later borings have shown that the soil on which the embankment was built was fine sand and coarse silt. The same soil conditions are known to be general in this area, so there are good reasons for believing that the soil involved in the large slide was also fine sand and coarse silt.

MECHANISM OF FLOW SLIDES

Based on a study of slides of the above described type as observed in Norway and in other countries, an attempt has been made to explain how these slides develop and propagate. According to this explanation the mechanism of sliding is as follows:

The slides start with an <u>initial slide</u>. In many cases the first slide is initiated by a man-made fill. This was thus the case in Orkanger, Trondheim (1930), Hommelvik and Finnvika. The time of occurrence of the initial slide frequently coincides with a low tide, which corresponds with the time of maximum degree of instability. In other cases the initial slide occurs in such a large depth of water that very little is known about what might have initiated the first slide. Most likely the initial slide occurred in a slope that was being oversteepened by the accumulation of material carried into the fjords by rivers.

The available evidence indicates that, at least in all the Norwegian cases, the initial slide was the result of the shear stresses exceeding the shear strength of the soil in the slope. These initial slides could therefore have been predicted by an adequate soil mechanics analysis provided the conditions were known in advance. Thus, there is no mystery involved in the initial slide. In countries with earthquakes it happens frequently that an initial slide in a slope in loose fine sand will occur as the result of a combined effect of a static shear stress and a sudden increase in pore pressure caused by the increase in compressibility resulting from the shaking by an earthquake. It is likely that a shake from blasting will have the same effect.

If the initial slide involves large quantities of saturated loosely deposited fine sand and silt it will be followed by a flow slide. It is a characteristic feature of loosely deposited fine sand and silt that a straining beyond shear failure is accompanied by a very dramatic loss in strength (Andresen and Bjerrum, 1967). What happens at a shear failure is that the structural arrangement breaks down and the grains will tend to consolidate towards a more dense configuration. In saturated sands such a consolidation requires, however, the expulsion of a volume of water and until this has occurred the sand mass assumes the character of a liquid with a low viscosity. The most characteristic feature of the slides described above is thus that the slide masses emerging from the initial slide behave as a liquid and therefore disappear downslope in a flow slide.

The immediate consequence of the change of the slide masses to a viscous liquid is that they flow away leaving the faces of the slide scar unsupported. These faces will in turn fail and flow away and in this way, following an initial slip, the slide will develop retrogressively slice by slice. A retrogressive slide will in many cases have the tendency to increase its width behind the initial slide in accordance with the presence of loose soil deposits. Even wide horizontal areas may be involved in the slide by such a retrogressive slide development. The rate of development of a retrogressive slide may vary from a few hundred meters to several kilometers per hour.

The mechanism of such a retrogressive flow slide is in many respects similar to that of the slides in the Swedish, Canadian and Norwegian quick clays (Bjerrum 1954), indicating that their development and dimensions are the consequence of the loss in strength after failure of the soil involved. In these flow slides as well as in the quick clay slides, the dimensions of the final slide are disproportionately large compared with the size of the initial slide.

Another consequence of the change of the slide masses to a viscous liquid is that when flowing down-slope they may cause severe erosion. When a mixture of soil and water flows over an area above water level in general little or no erosion will generally occur. The upper layer of top soil with its vegation possesses a cohesion sufficient to resist the shear forces of a moving mud. Under-water such a top layer is normally missing and where the soil is a fine sand or a coarse silt with practically no cohesion a flow of liquified soil will result in very severe erosion. The susceptibility to erosion of unprotected fine sand or coarse silt is a problem well known to engineers who have worked with hydraulic dredging or with the deposition of tailings from mines.

It is therefore not surprising that when a liquid sand mass escapes from an initial slide and flows downhill over a subaqueous sand or silt slope it will erode deep canyons therein. As the flow slide proceeds downhill it will thus grow in volume and be supplied continuously with new liquid sand masses picked up by erosion or flaking off from the walls of the canyon.

As the liquid sand masses continue to descend, the walls of the canyon will lose their support and fail, thus initiating a new series of retrogressively developing slides which in turn will cause a further extension of the slide and add further volumes of liquid sand to the flow slide.

It goes without saying that the erosion reaches a maximum when a flow slide descending from a slope reaches the bottom of the fjord and is there enforced to change direction. In such cases the liquid sand will attack the toe of the slope on the opposite side of the fjord. If this slope consists of loose sand and silt the result will be to initiate a new series of retrogressive slides again leading to an enlargement of the volumes involved and a further supply of liquid sand to the flow slide.

Most of the damage a flow slide will create will obviously take place in the early period of its life and it becomes less dangerous when it is finally flowing at the bottom of the fjord at a relatively small gradient. Provided the fjord is wide enough and the gradient small, the flow slide will gradually be spread so thinly and its velocity will decrease so much that the sand will "freeze" (Terzaghi 1956). This means that the liquified sand will consolidate and obtain the character of a firm sand deposit. The slide has thus come to a halt.
If the topography and the gradient of the bottom of the fjord is such that the flowing masses will continue to move fast enough to prevent a spreading and a consolidation the liquified silt or sand may continue to move over very long distances (Vogt 1943, Heezen and Ewing

1952). Obviously when flowing over areas with small gradients the erosive power of the flow slide is small. However, where the topography of the fjord forces the stream to change direction, erosion will occur in the toe of the obstructing slope and a new series of retrogressive slides may thus be initiated.

EXPLANATION OF NORWEGIAN FLOW SLIDES

In the light of the mechanism of sliding described above, the events observed at the six Norwegian slides may be explained as follows:

In Orkdalsfjorden the initial slide, slide A in Fig. 2, was the result of loading with an embankment an already highly stressed underwater slope in fine sand and silt. An artesian water pressure in the rock beneath the slope may have contributed to its instability. As the slide masses flowed down the 250 m high and relatively steep slope it cut a deep canyon into the sand. A series of retrogressively developing slides were initiated by slides from the walls of this canyon and these propagated into the estuary in the inner part of the fjord and caused first the subsidence shown as slide B in Fig. 2 and then the failure at slide C. On its way out into the fjord the liquified masses of sand probably initiated a new series of retrogressively developing slides by erosion of the toe of the slopes along the fjord. The result was that the flow slide repeatedly received new supplies of liquified sand which kept it moving. The occurrence of such slides were, however, only observed at the two locations where cables crossed the fjord.

The slide in the harbour of Trondheim in 1888 was initiated by an initial slide at great depth of water. No explanation can be given for the occurrence of this slide, but it is known that the slopes in the area were locally rather steep. In addition boats arriving in the harbour frequently dumped their ballast in this area. From the initial slip the slide developed retrogressively into the sand slope and first came to a halt when it reached more dense sand deposits below the filled-in areas at Brattøra. The flow slide following the slide is not known to have caused additional damage.

The slide in Trondheim in 1950 may similarly have been started by an initial slide in the slope, some distance from the shore line. It is, however, most likely that the initial slide was the result of an overloading of the clay beneath the fill and that the subsequent much larger slide outside Ilsvika was the result of erosion caused by the slide masses from the initial slide, followed by a series of retrogressively developing slides.

The slide in Hommelvika was beyond any doubt initiated by an overloading of the fine grained foundation soil beneath the fill and the propagation was the combined effect of erosion by the slide debris and a retrogressively developing slide activity.

The events occurring in Follafjorden in 1952 were started by an initial slide which took place in a great depth of water and probably near the toe of the slope. This initial slide may very well have been initiated by the dumping of fill from the dredging operations. The initial slide started a series of slides gradually encroaching into the slope to its rear and finally reaching the anchor of the dredger. When the slide masses from this series of slides descended the slope and were forced to change direction at the deepest point of the fjord, very severe erosion occurred. From the scars of this erosion a new series of slides was initiated which gradually involved in the movements the estuary in the interior part of the fjord. It was the flow slide from this very voluminous slide which impinged upon the anchors of the dredger and for the second time moved it out into mid-fjord.

The slide in Finnvika is very similar to the slide in Hommelvika only the dimensions are much greater. The initial slide was probably triggered off by the failure of the fill but high pore pressures in the nearby rock beneath the fill may have played a role in the instability.

CONCLUSION

A survey of available evidence from some slides in Norwegian fjords has demonstrated that disasters of tremendous dimensions can occur in subaqueous slopes in fine sand and coarse silt.

The explanation of why these slides so frequently reach such dimensions can be found in the two characteristic properties of these materials:

The first property is the complete loss in strength after a shear failure which is so characteristic for loose fine sand and coarse silt. As the result of this property the slide masses assume the character of a viscous liquid and, in the first place, flow downwards from the slide scar and possibly initiate new slides by erosion. In the second place, the disappearance of the slide debris means that the faces of the slide scar are left unsupported, involving the risk of an extension of the slide in an uphill direction by a retrogressive, slice by slice, development.

The second property of submarine deposits of fine sand and coarse silt responsible for the disastrous character of the slides is their exceptionally high erodability. The reason why these deposits are so easily attacked by erosion is partly the lack of cohesion of fine sand and coarse silt particles and partly the lack of a protective cover of top soil and vegetation in submarine deposits. The consequence of the high erodability is that if a flow slide descends over this type of deposit, it will cut deep canyons into the slopes and undermine any obstruction which deflects it from its original path. The scars of such an erosion can lead to the development of a new series of retrogressive slides which can contribute both by extending the slide and by adding further liquid sand to the flowing masses.

In the postglacial deltas and estuaries occupying the head of the fjords in middle Norway, the fine sand and silt slopes frequently stand relatively steeply. In most cases the deposits are continuously growing as a result of accumulation of sandy and silty material being carried out into the fjords by the rivers. Under these conditions even small man-made fillings may initiate a slide of considerable size. A factor which may contribute to the instability of the submarine slopes in these fjords is artesian pore pressure conditions originating from high water pressures in the fissures of the bedrock beneath the deposits.

SYNOPSIS

The paper summarizes the observations made during six very large submarine slope failures which have occurred in fine sand and coarse silt deposits occupying the head of the fjords in the middle part of Norway.

An interpretation of these slides demonstrates that their disastrous character and large dimensions are the result of the complete loss in strength that these materials undergo when involved in a slide and the erosion occurring when the liquified sand masses descends from the initial slide cavity.

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TEXT OF FIGURES

TEXT OF PHOTOS

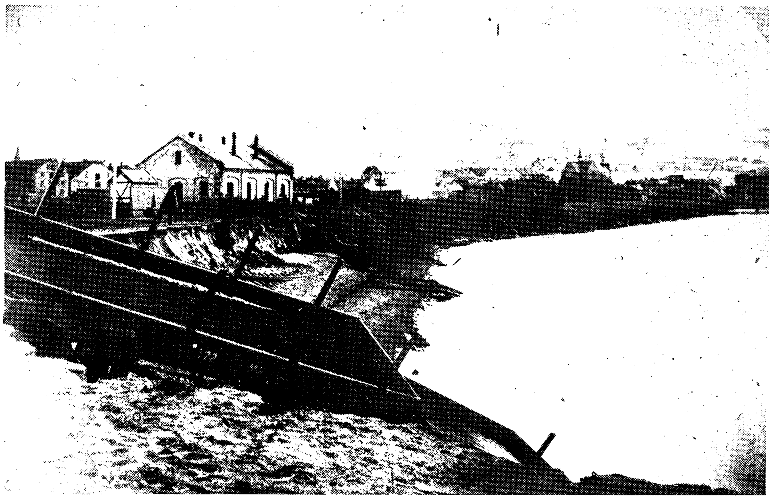


PHOTO 1 The slide in Trondheim 1888
Seen from north

PHOTO 2 The slide in Trondheim 1888
Seen from south

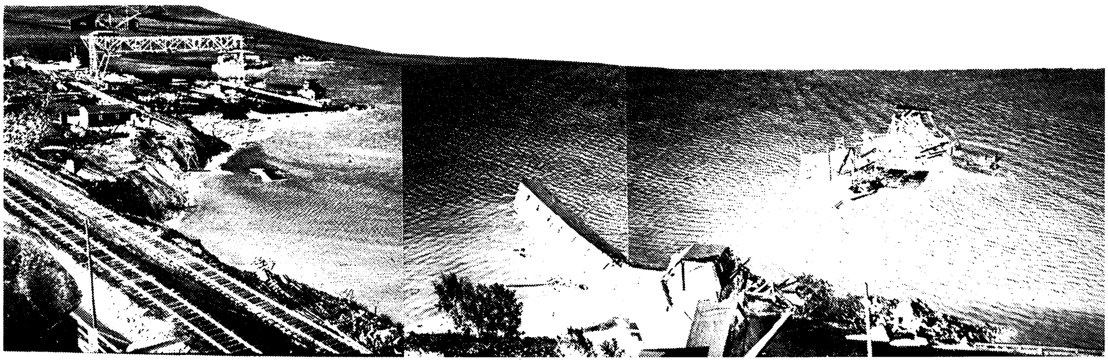


PHOTO 3 The slide in Trondheim 1950

PHOTO 4 The slide in Hommelvika 1942

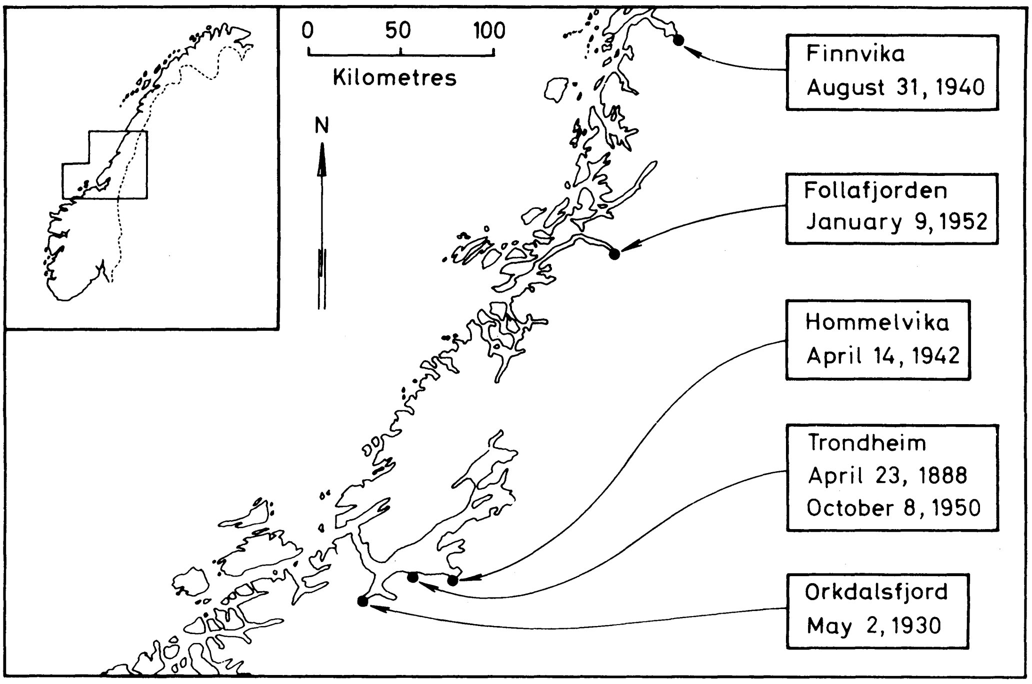


Fig. 1. Map of middle part of Norway
with location of the six described slides.

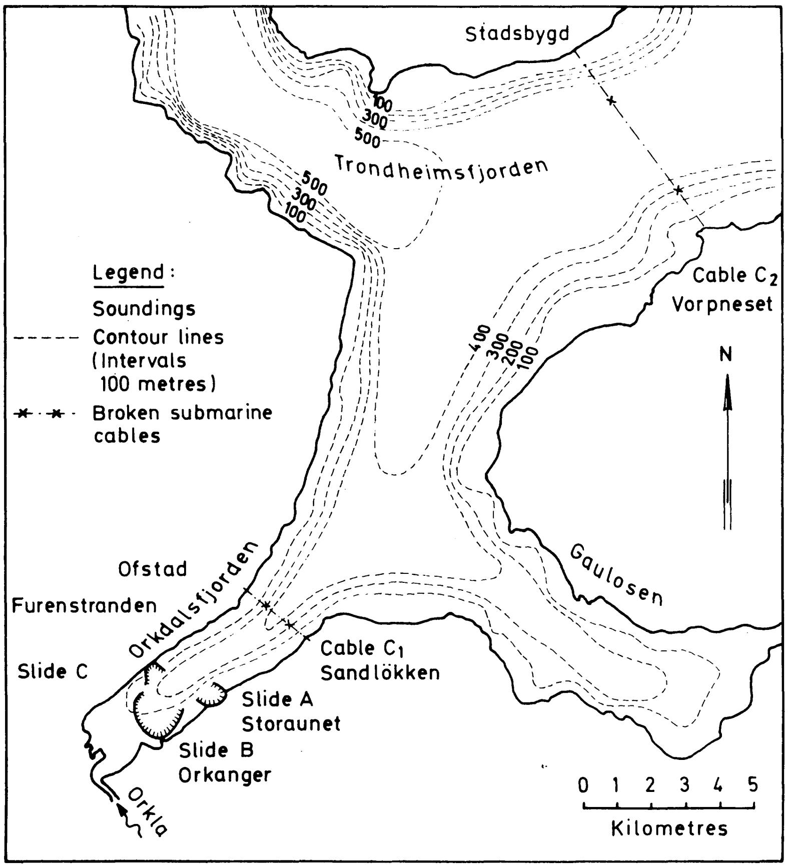
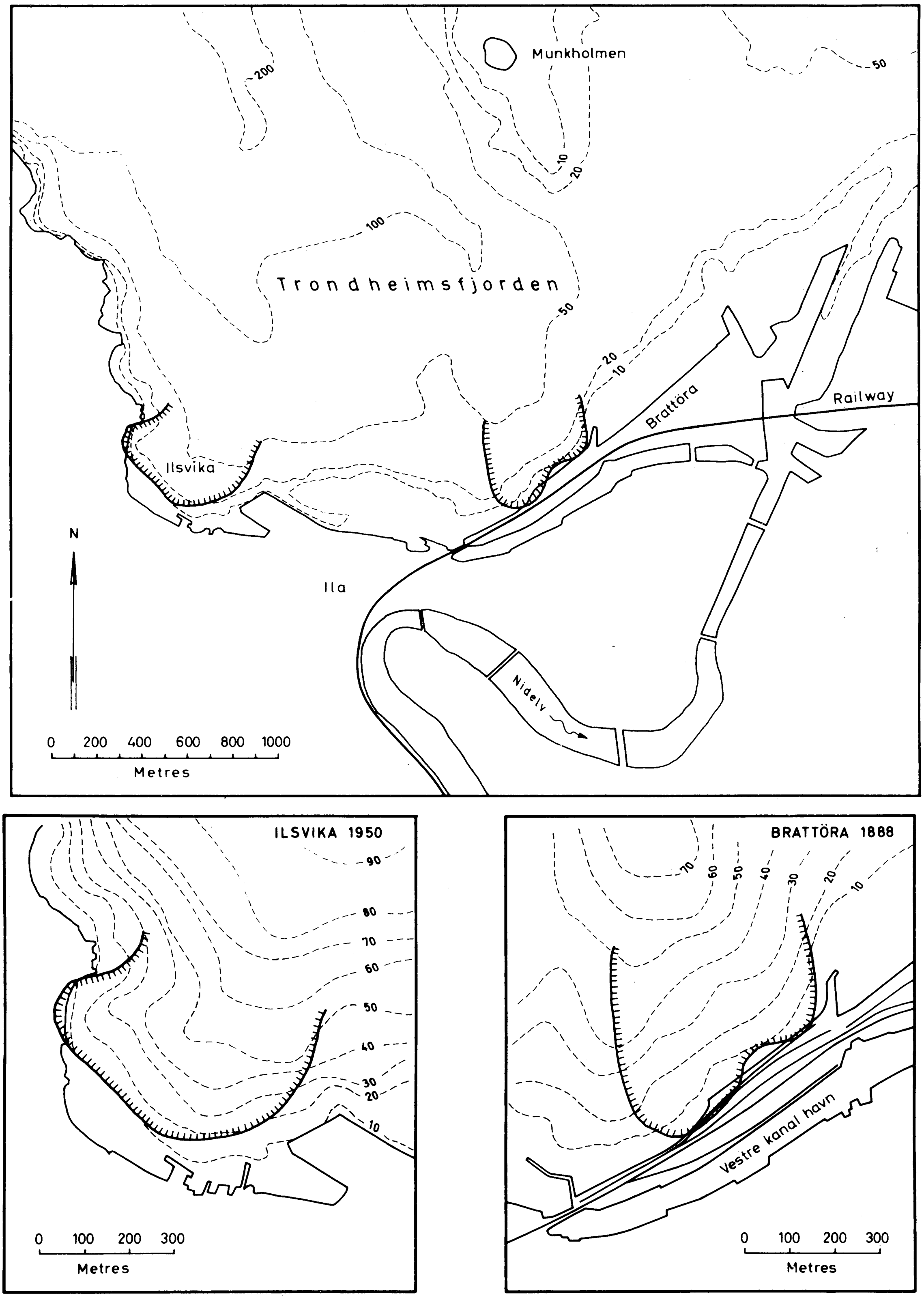


Fig. 2. Slide in Orkdalsfjord,
May 2, 1930 (Terzaghi 1956)



(Skaven Haug 1955)

Fig. 3. Slides in the harbour of Trondheim on April 23, 1888 and October 8, 1950

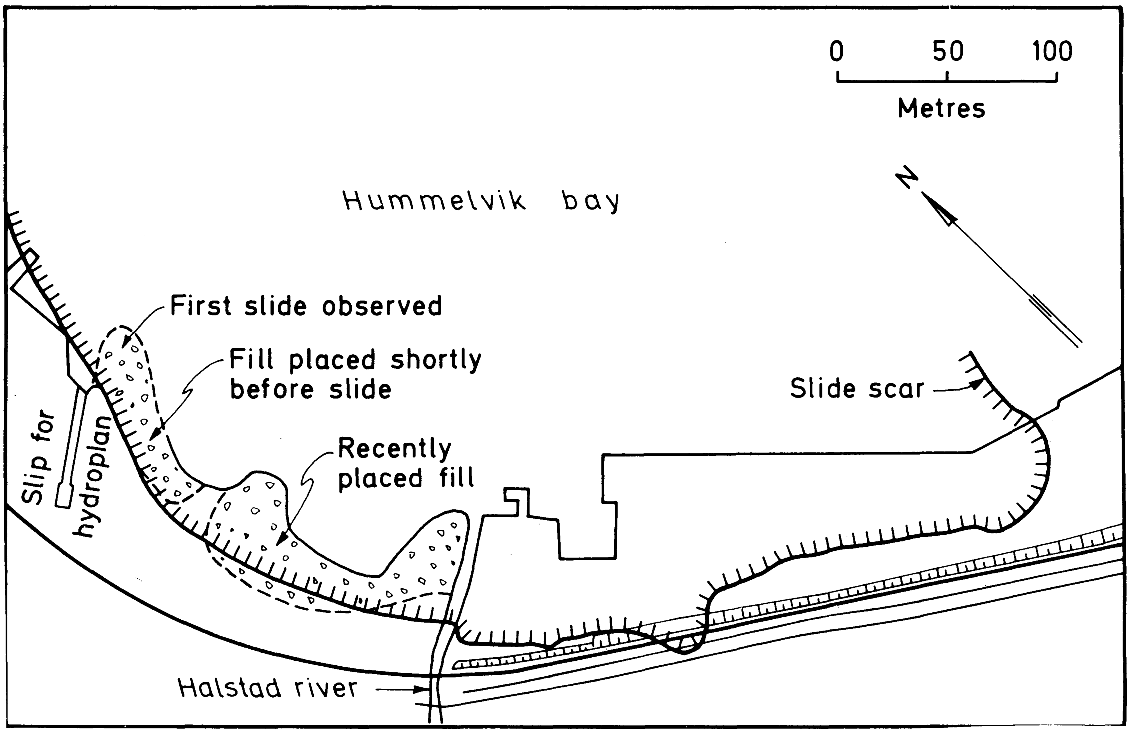


Fig. 4. Slide in Hommelvika, April 14, 1942

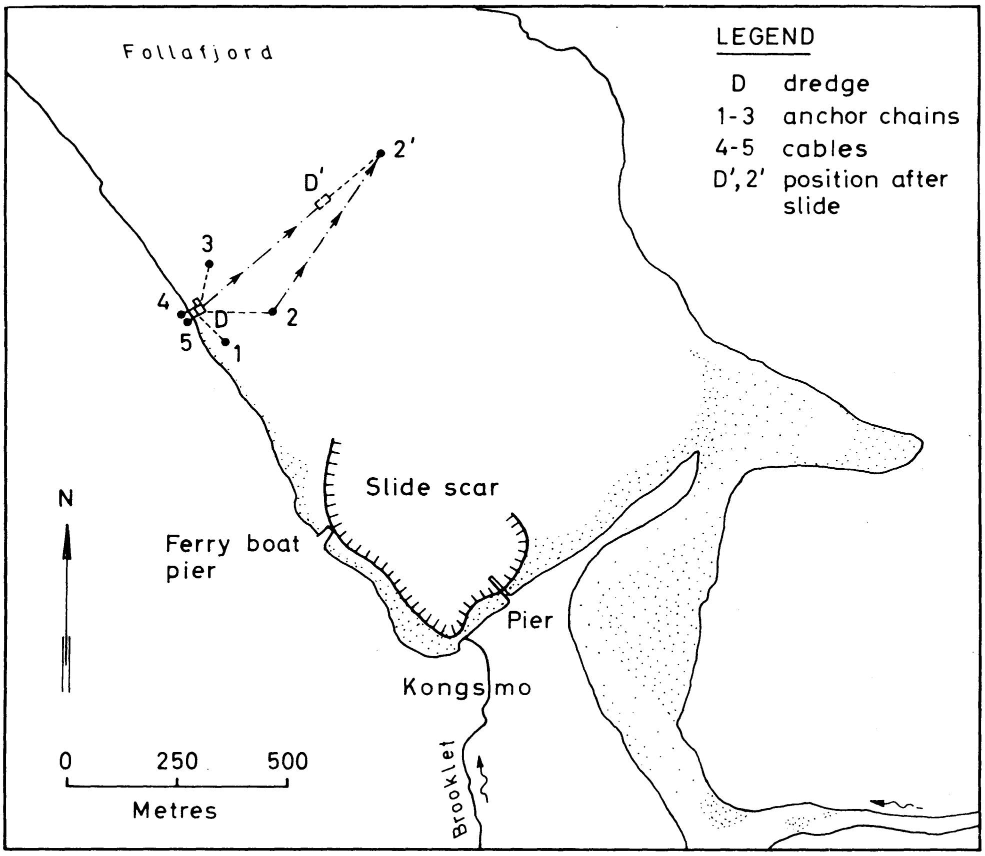


Fig. 5. Slide in Follafjorden, January 9, 1952

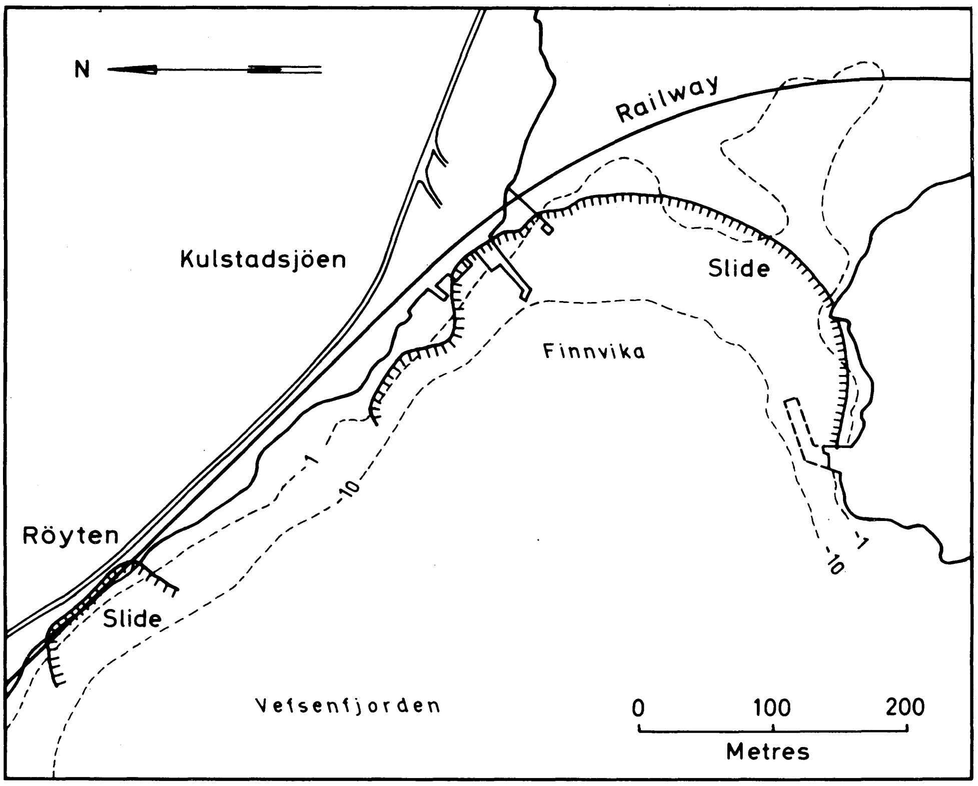


Fig. 6. Slide in Finnvika, August 31, 1940