Statens vegvesen
Norwegian Public Roads Administration

A feasability study
– How to cross the wide and deep Sognefjord

SUMMARY

REPORT

Projects Division

Norwegian Public Roads Administration - Western Region
Projects Division
Dated: March 2011

Norwegian Public Roads Administration

The Norwegian Public Roads Administration is responsible for the planning, construction and operation of the national and county road networks, vehicle inspection and requirements, driver training and licensing.

This report is a shortened version in English of the original report in Norwegian, seen above.

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INTRODUCTION

The ultimate goal for coastal highway E39 between Kristiansand and Trondheim is to replace the eight ferry crossings with fixed links using tunnels or bridges.

The Western Region of the Norwegian Public Roads Administration has initiated a series of technology development studies to investigate the possibilities for crossing these very deep and wide fjords. The Sognefjord crossing has been chosen for pre-feasibility studies, this crossing being 3700 metres wide with depths down to 1300 metres.

It is hoped that studies of this extremely challenging crossing, combining experience and technology from offshore oilfields and other places, will solve many problems for crossing narrower and shallower fjords later.

The final aim of this study is to present concrete alternatives for fixed links, excluding subsea tunnels, which would be part of other feasibility studies.

This pre-feasibility study has been organised by the Project Division of the Norwegian Public Roads Administration, Western Region.
Members of the project group have been:

- Lidvard Skorpa, head of project, Western Region
- Bjørn Isaksen, Road Directorate
- Kristian Berntsen, Road Directorate
- Jorunn Hillestad Sekse, Western Region
- Håvard Østlid, private consultant
- Bernt Jakobsen, COWI AS/ private consultant
- Svein Erik Jakobsen, Dr. Ing. A. Aas-Jakobsen A/S

The first part of this feasibility study was two “think tank” seminars where key persons were invited to discuss as many aspects as possible of submerged floating tunnels, floating bridges, suspension bridges and any combination of these alternatives.
This work was completed during summer 2010.

Since these seminars, the proposed alternatives and other new alternatives have been studied and developed further by the project group. Key elements in these studies have been the most central issues, ranging from safety, geometrical details and dynamic considerations to constructability.

This report presents a short overview of the pre-feasibility studies and recommendations for further work.

SUMMARY AND RECOMMENDATIONS

The project group considers the results from the seminars and initial feasibility studies to be very encouraging. These results indicate that several alternatives for crossing the Sognefjord are technologically possible. Further work should now concentrate on bringing forward necessary documentation to verify this as far as possible at this stage of the development.

Results from these studies have already proved to be very useful for fjord crossings in other locations.

The project group has concentrated on three principal alternatives. The most promising ones use floating pontoons or similar elements as foundations. A floating bridge is one such alternative; another is a submerged floating tunnel. The latter type of structure has not yet been built anywhere, but many plans exist.

The third main alternative is a suspension bridge or similar construction spanning the width of fjord. This would be almost double the length of the longest existing bridge span in the world.

The challenge to these structures is to withstand the horizontal forces from wind, currents and waves in long span situations.

For further study of crossing the Sognefjord, the group recommends the three bridge alternatives as shown in the table below:

Bridge type	**Alternative**
Floating bridge	High level, on pontoons, shore anchored only, mid-fjord ships passage
Floating bridge	Shore anchored, high level bridge near shore for ships passage
Floating bridge	Combined with submerged floating tunnel as ships passage
Submerged floating tunnel	Two parallel cross connected tubes in horizontal curve with surface pontoons
Submerged floating tunnel	Single tube in horizontal curve with surface pontoons and horizontal anchor cables to shore
Suspension bridge type	Single span across the fjord
Suspension bridge type	Foundations on pontoons, shortening the span

Based on the table above, further work will concentrate on developing and possibly documenting critical elements in the proposals.

In addition the group recommends that studies on deep sea foundations be initiated as soon as possible.

1. GENERAL INFORMATION ABOUT ALTERNATIVES

The alternatives presented in the following are only a selection of the results from the seminars and later work by the project group.

The various bridge alternatives are organised according to principal construction type. Comments and discussions are not limited to the Sognefjord crossing at Lavik-Oppedal, but include some observations about the other “extreme” fjord crossings.

This report presents the view of the project group, with important emphasis on the the factors shown below:

- Safety for traffic and structure (ships’ impact, redundancies, known hazards and so on)
- Constructability (ability to provide capacity to withstand all relevant loads and also necessary technology development)
- Robustness of structures at various site specific conditions (widths and depths, waves, wind and currents, ships traffic and so on)
- Least possible hindrance for future passage of ships and minimum deviations from applicable present rules and regulations
- Robustness and simplicity for future control, operation and maintenance

The proposed work plan and priorities have been drawn up using experience from deep sea foundations in connection with bridge constructions. It is important that the alternatives put forward are considered realistic in light of existing requirements, rules and regulations.

The project group has concentrated its efforts on presenting and discussing relevant problems and challenges for each of the alternatives. Some preliminary calculations have been made to identify special areas needing further work at this stage of the various alternatives. This work, which was aimed at identifying safety or technical problems at an early stage, has resulted in the rejection of a number of proposals – at least for the time being.

The volume of future traffic has been used to establish the necessary geometry and other requirements for the traffic situation in the year 2040.

These crossings, which are intended to be open to all groups of users, satisfy the requirements of universal design.

2. FLOATING BRIDGE

2.1 Recommended priorities

The following alternatives will be developed further.

Crossing the Sognefjord

Because of the great depth of the fjord, more than 1250 metres at the proposed place of crossing, it has been decided not to have any fixed foundations on the fjord bottom.

The width of the fjord, 3700 metres, calls for special measures to ensure sufficient horizontal strength and stiffness of all structures withstanding movements and forces from currents, waves and wind.

The two most promising alternatives for crossing at Lavik-Oppedal are briefly described in the following:

<u>Floating bridge with high bridge mid-fjord for ships passage.</u>

Fig.1 The “bucket handle alternative”

This is a bridge with columns on pontoons, where the bridge is curved horizontally with descending height towards the shorelines. This structure, which is sometimes referred to as the “bucket handle alternative”, provides the necessary clearance for future cruise ships.

Although this alternative has not yet built anywhere, it is believed to handle the horizontal forces adequately.

As a starting point, single pontoons are considered to provide enough stiffness across the bridge alignment and, when placed parallel to the shores, will experience minimum effect from conditions at sea.

Alternatively, secondary supports may have to be provided in a different way. An example is shown in Fig. 2; introducing separate bridge decks will also increase horizontal stiffness.

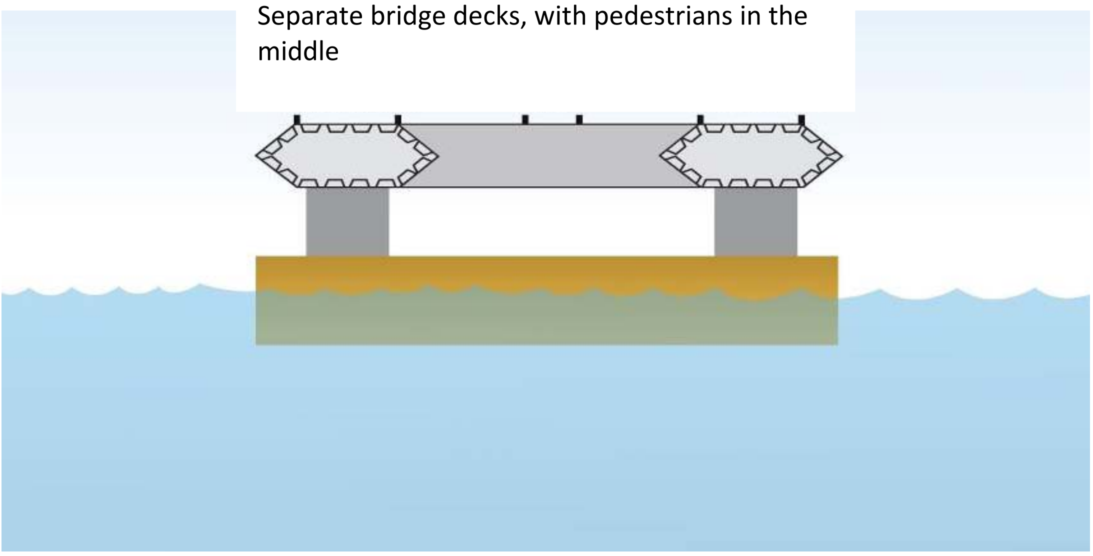


Fig.2 Principle sketch, separate bridge decks and pedestrian lane

<u>Floating bridge with a high bridge or similar construction close to shore</u>

This alternative is the same as an existing floating bridge: the Nordhordlandsbru near Bergen on the west coast of Norway. This bridge has a high bridge from land to a foundation in the sea at a depth of 35 metres and a total bridge length of 1614 metres. It is the only floating bridge with no anchors except at landfalls.

Fig. 3 The Nordhordlandsbru, opened in 1994

The crossing of the Sognefjord will require some rock blasting to create the necessary space for ships to cross under the bridge.
The bridge design can be seen in fig. 4.

Fig. 4 Floating bridge with cable-stayed bridge over passage partly created by rock blasting

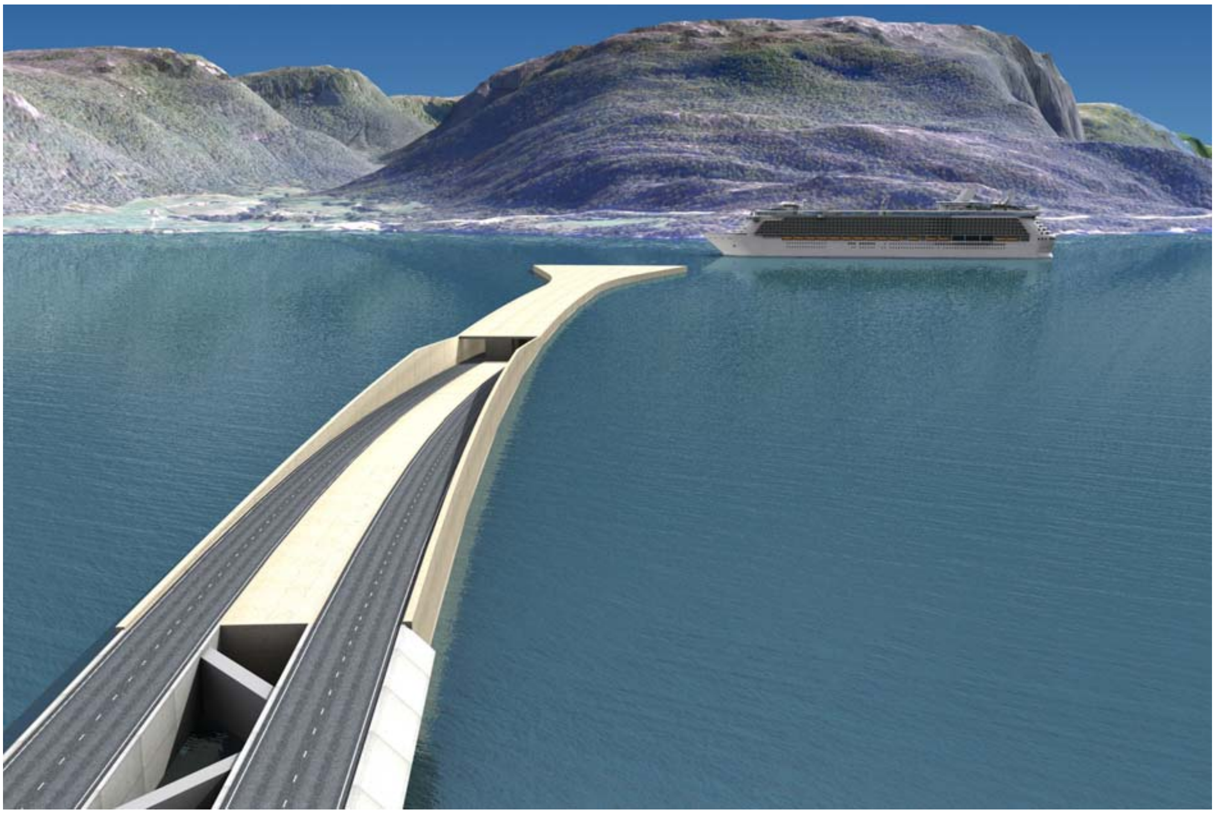
One important point is how deep it is possible and economically viable to place the foundation of the bridge and whether it is possible to avoid any type of anchoring, horizontally or vertically.
A characteristic of this alternative is the long ramp down from the bridge to the floating bridge section. If necessary, greater horizontal stiffness may be obtained by using separate bridge decks.

Floating bridge and submerged floating tunnel with pontoons

Fig. 5 Floating bridge with pontoons for entering the submerged floating tunnel at mid-fjord

Further work is necessary to study the combination of floating bridge and large pontoons taking the traffic down to the submerged floating tunnel and up to floating bridge level. Another alternative might be this arrangement near the shore, then using only one pontoon and connecting the submerged floating tunnel at depth with a rock tunnel.

The floating bridge could also connect to a submerged floating tunnel through a floating structure and then approach the shores in two separate tunnels, creating a Y to provide extra stiffness to the construction.



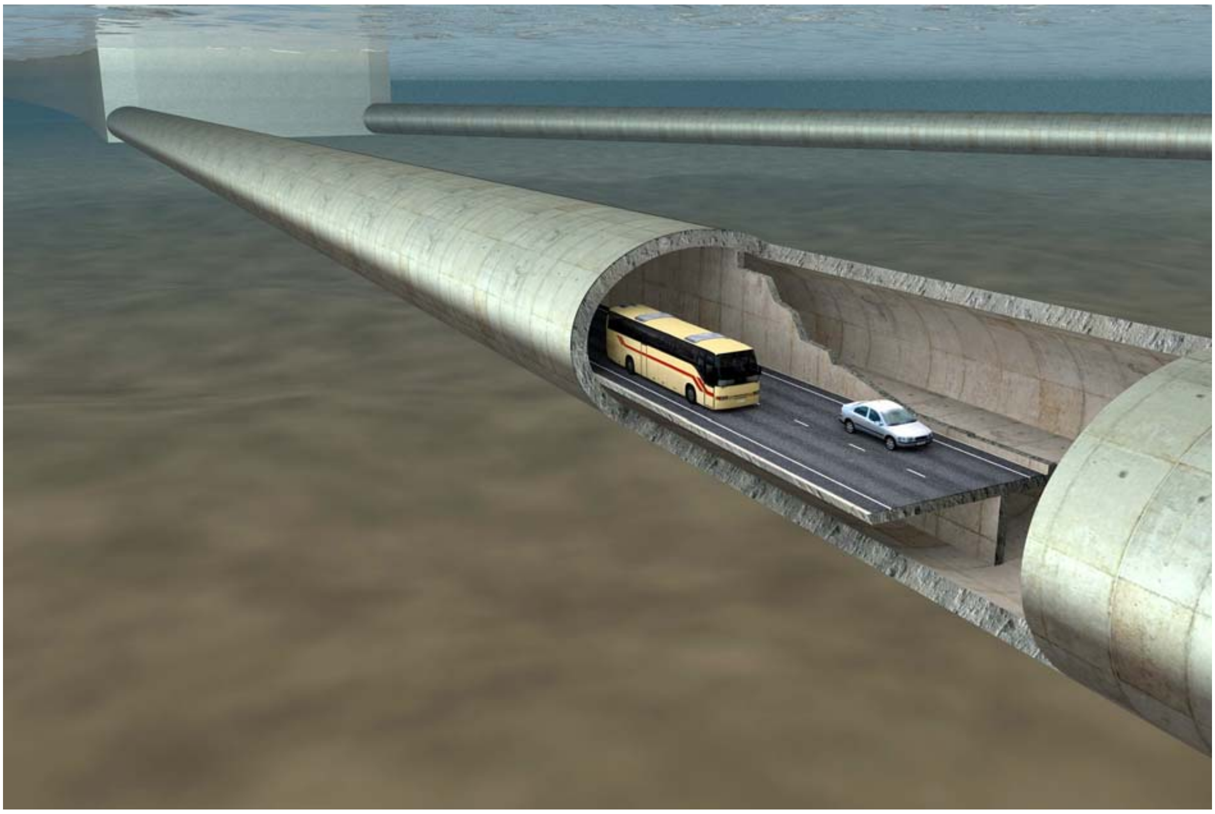


Fig. 5 Floating bridge connecting with Y-shaped submerged floating tunnel

General comments regarding other fjord crossings

Most of the other places for crossing fjords on the west coast would be different from the Sognefjord crossing; some would be shorter and other crossings would be considerably shallower.

Optimal locations of crossings could favour alternatives with crossings in a straight line instead of curved, with simpler foundations at shallower depths and so on.

Floating bridges directly exposed to the open sea would present substantial problems and are not recommended in this study.

With these arguments in mind, a large number of other fjord crossings may be feasible, and in these instances the local environments will play an important role.

2.2 Necessary clarifications and further studies

The table below presents a limited number of themes and actions deemed necessary for further development of the alternatives.

Themes	Actions
Safety	Acceptable risk of: - Loss of lives - Loss of construction - Loss of ships Which extreme load situations should be considered Impact of climatic changes
Road standards etc.	Separate pedestrian/cyclist lanes Height of sailing clearance Studies of pontoon road spiral and movable floating sections
Special studies	Ship impact studies and ship sailing paths
Special studies	Statistical and dynamic analysis and preliminary design to check for constructability and main dimensions
Special studies	Overall construction and installation methods

3. SUBMERGED FLOATING TUNNEL (SFT)

3.1 Recommended priorities

The following alternatives for a submerged floating tunnel crossing are tentatively presented:

Crossing the Sognefjord

At the chosen location of crossing, water depths may be as great as 1250 to 1300 metres, and anchoring to the sea floor is considered impractical.

The width of the fjord, 3700 metres, requires special design to secure sufficient horizontal strength and stiffness and also limit movement to acceptable values.

One of the most promising alternatives is shown in fig. 6.

<u>Double tunnels in horizontal curve, using pontoons and crossover tunnels for stiffness and also escape facilities.</u>

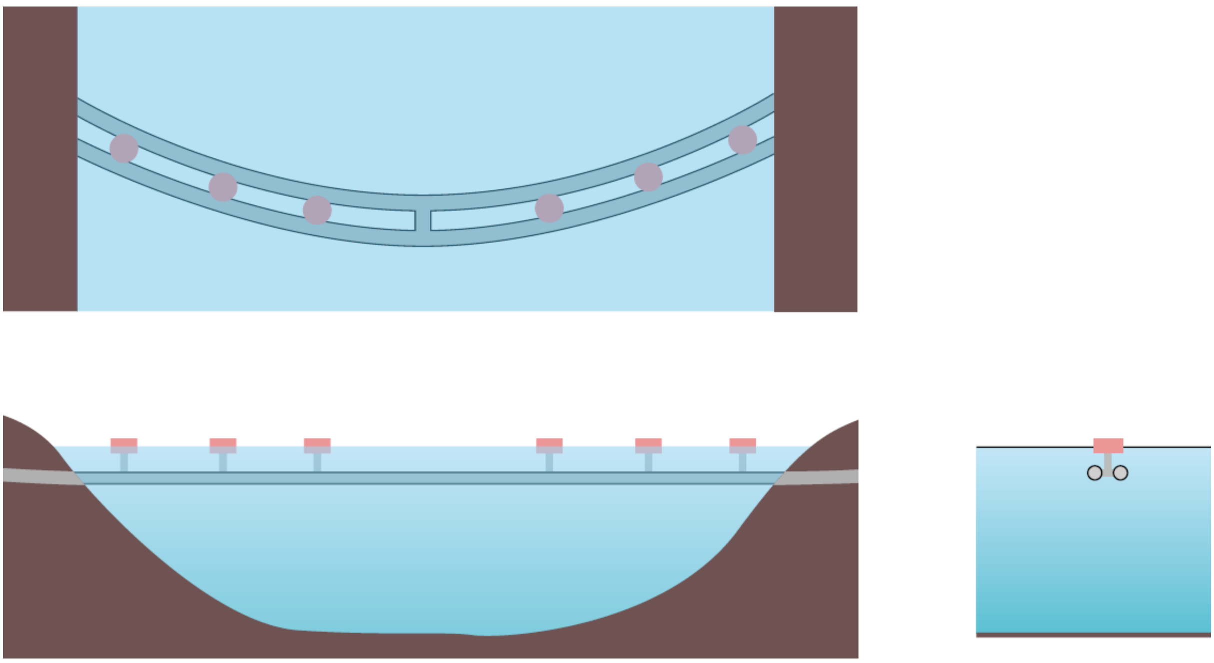


Fig. 6 Double tubes in horizontal curve, using pontoons and crossover tunnels for stiffness and also escape facilities.

Each tunnel has two lanes, ensuring traffic flow during maintenance and accidents.
If extra lay-bys are required for accident preparedness, they may be located in the area of the crossover tunnels.

Alternatively, there may be one large tunnel for traffic and a smaller parallel tunnel for pedestrians and cyclists.

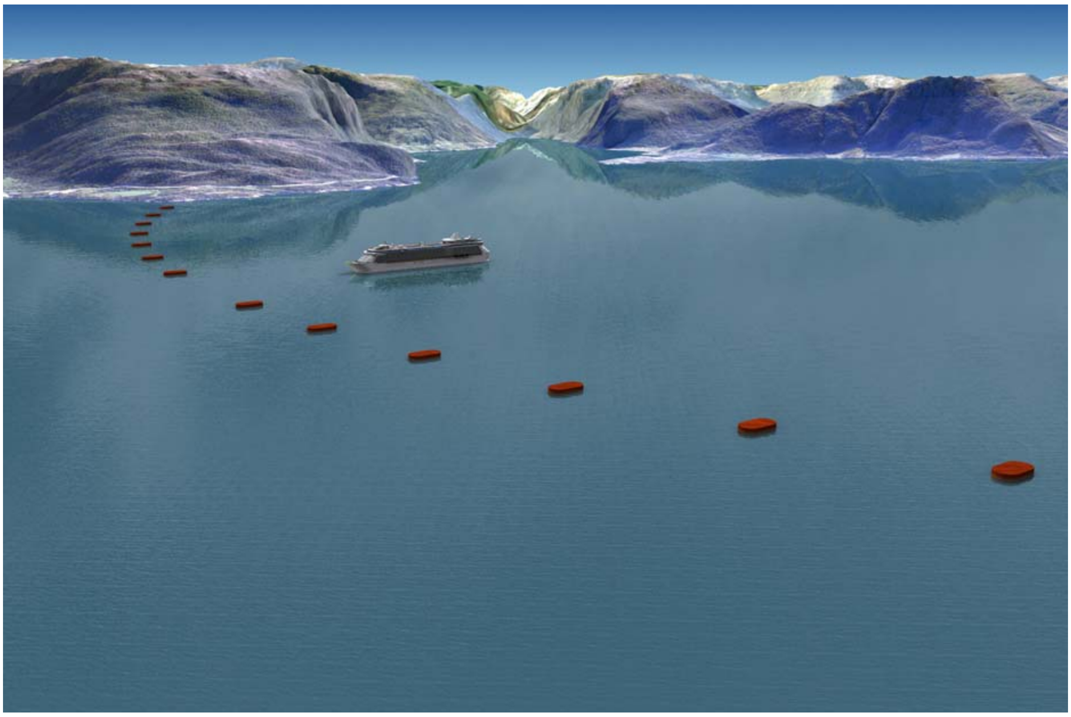


Fig. 7 Free passage between pontoons, but vulnerable to collision with ships

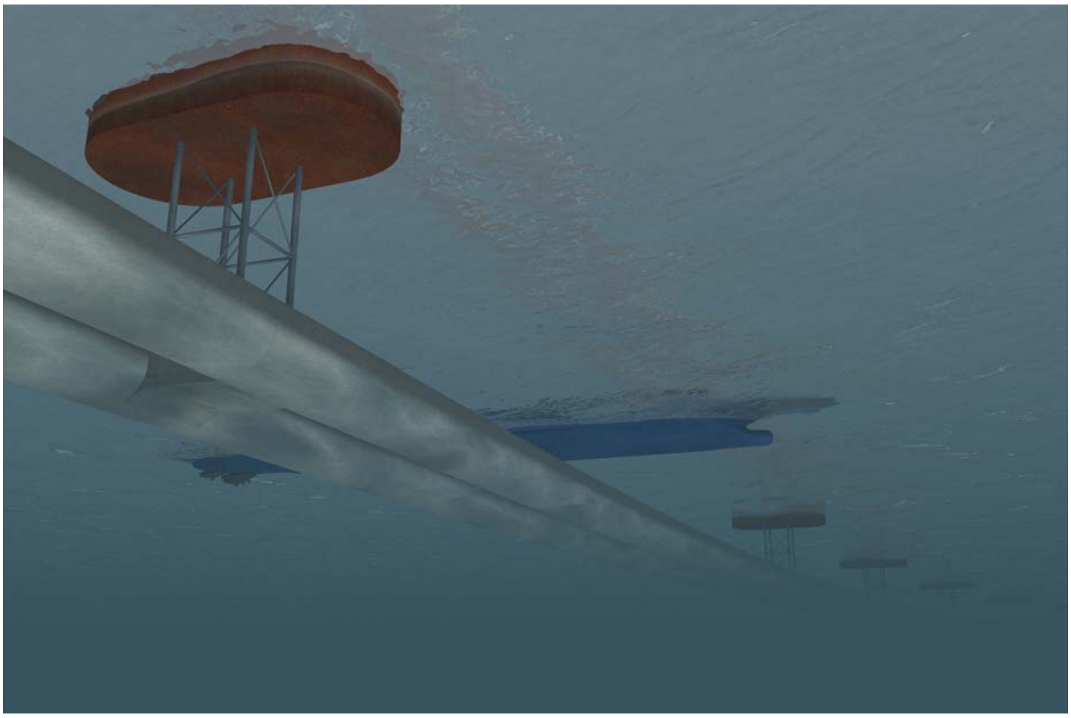


Fig. 8 Submerged floating tunnel seen from underneath.
The weak link construction between tunnels and pontoons produces necessary redundancy.

This alternative is a relatively simple constructional system having sufficient potential for adequate stiffness and strength to withstand loads and movements from wind, waves and currents.

<u>Single tunnel submerged floating tunnel with pontoons and horizontal anchors at ¼-points to shores</u>

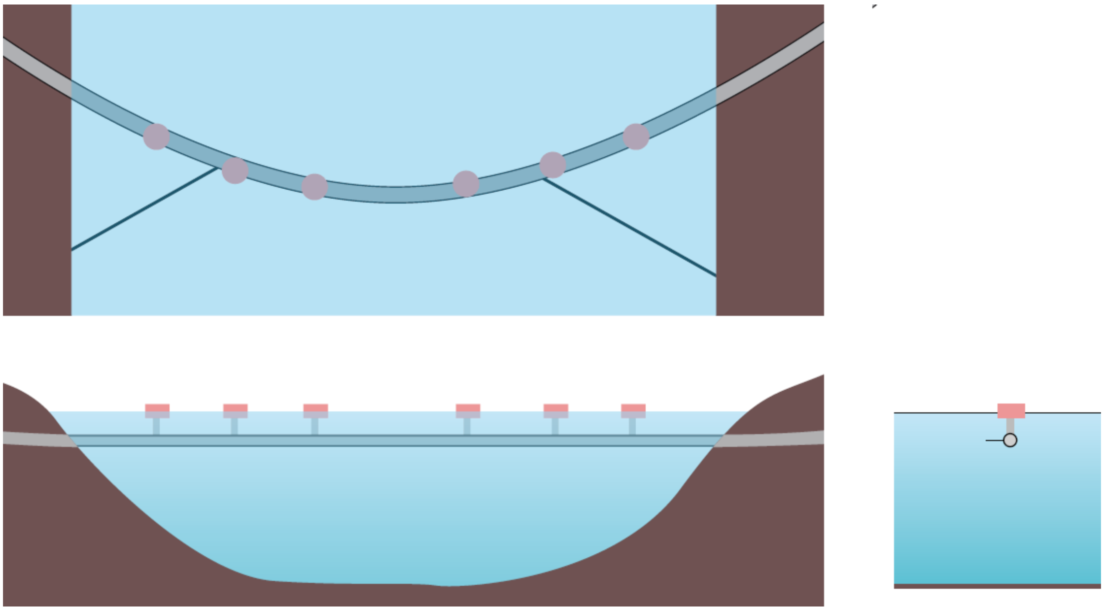


Fig. 8 Single tunnel, pontoons and horizontal anchors

The single tunnel obtains vertical stiffness from sufficiently large pontoons and horizontal stiffness from the curve and the horizontally anchored cables. In some cases these cables may be used in a different configuration, possibly on both sides of the tunnel. In all cases these cables have to be in tension and adjustable over time.

This system may be a realistic alternative for crossings up to 2000 metres.

General comments regarding other fjord crossings

Most of the other relevant places for fjord crossings on the west coast would be different from the Sognefjord crossing. Both water depths and widths of the crossings would be less, making crossings simpler to construct with anchoring down to the sea bottom.

Fjord crossings exposed directly exposed to open sea would require other solutions than proposed for the Sognefjord crossing at Lavik-Oppedal.

Submerged floating tunnel without pontoons, with adequate stiffness ensured both horizontally and vertically by inclined tethers to sea bottom

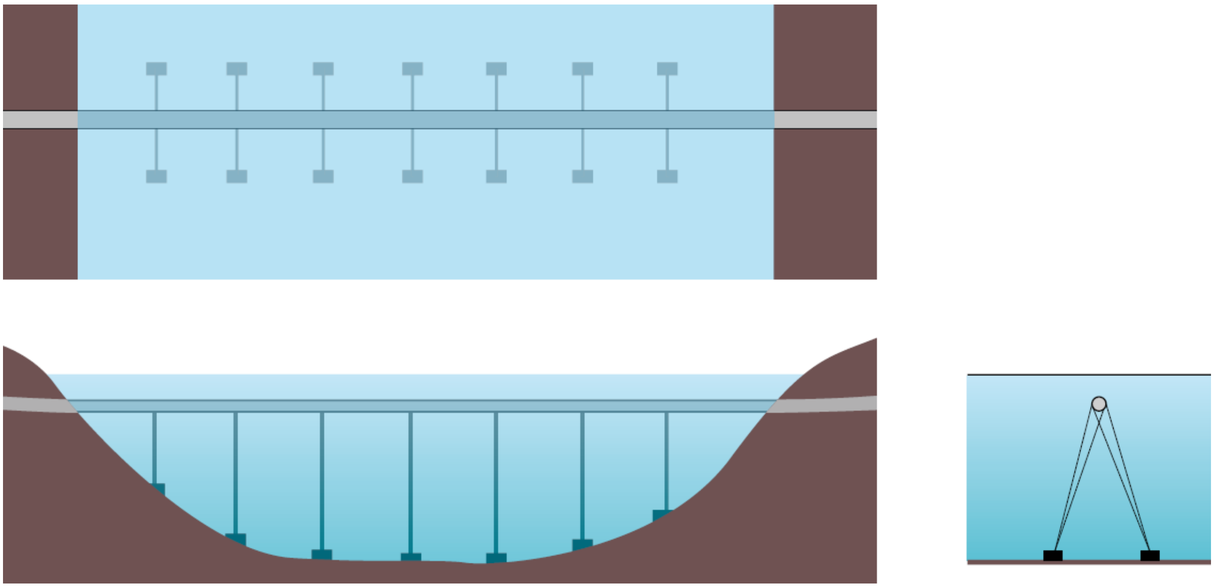


Fig. 9 Tethered alternative

The tunnel has to have sufficient buoyancy to maintain tension in the tethers at all times, while at the same time these forces should be balanced to avoid unnecessary overdesign.

The tethers will produce tension for the foundation, which calls for using some sort of caissons with a dead weight that is heavy enough, even if this will later cause settling and require adjustable tethers. Other methods for anchoring may be tension piles or vacuum caissons.

The heavy caisson anchor is regarded as the simplest and safest anchor. Its feasibility was proven in the Høgsfjord Project, which developed several designs in great detail.

This alternative is expected to be the most practical and safe for foundations where sea conditions are rough. It is also independent of the length of crossing.

3.2 Necessary clarifications and further studies

The table below presents a limited number of themes and actions deemed necessary for further development of the submerged floating tunnel alternatives.

Themes	Actions
Safety	Acceptable risk of: - Loss of lives - Loss of construction - Loss of ships Which extreme load situations should be considered Fire and explosions
Road standard etc.	Separate pedestrian/cyclist lane Width of ships passage Turn back possibility in single tunnels Accepted tunnel cross sections for single and double tunnel
Studies	Ship impact studies and ship sailing paths
Studies	Statistical and dynamic analysis and preliminary design to check for constructability and main dimensions
Studies	Overall construction and installation methods

4. SUSPENSION BRIDGE

4.1 Recommended priorities

<u>Suspension bridge crossing the fjord in a single span, 3700 metres</u>

Crossing the Sognefjord with a traditional type of suspension bridge is a great challenge. A main span of 3700 metres is about twice the span of the longest existing suspension bridge, Akhasi-Kaikyo in Japan, which has a free span of 1991 metres.

Extensive, sustained research and development over a period of perhaps 10-15 years will be necessary to accomplish the Sognefjord crossing. One key and highly complex issue in this connection is aerodynamic stability.

When a free span exceeds about 1500 metres, it may be necessary to change the cross section design presently used in this country. The required cross section would be separated by cross-braced road decks to improve the dynamic stability.

The distance between the lowest and highest point of the suspension cables is usually about 1/10 of the free span. In this case this would probably require a pylon height of 4-500 metres, which also would be great challenge to construct.

The cables would be produced by spinning on site. Several cable configurations would be considered with aerodynamic stability in mind. Normally, one cable on either side is used, but a cable or cables may also be positioned along the central axis of the bridge.

Suspension bridge with one or two pylons on pontoons

The cost of suspension bridges normally increases exponentially with the length of the main span. At the same time, the aerodynamic problems increase.

Reducing the main span may be possible if one or both pylons are founded on floating pontoons. Fig. 10 illustrates how this might be done.

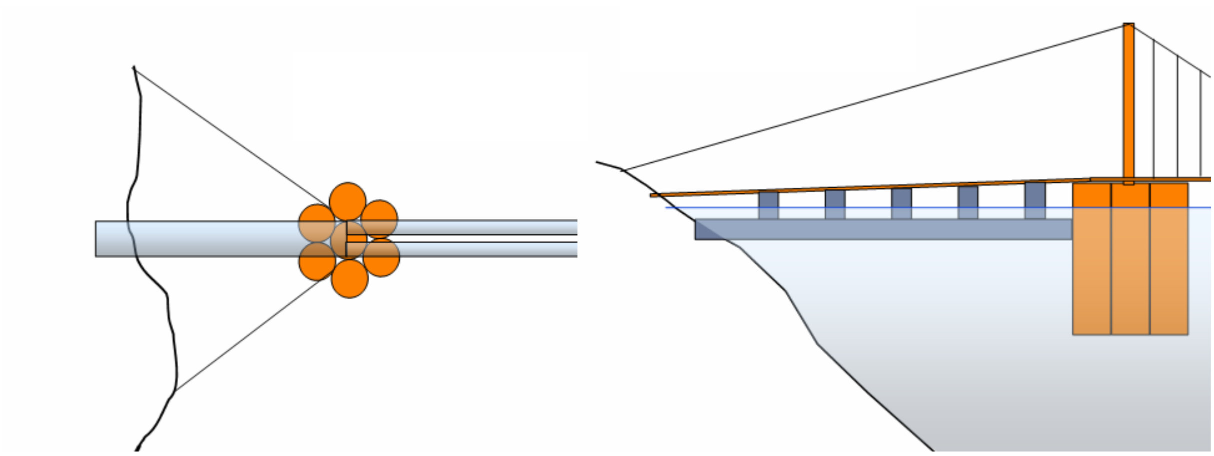


Fig. 10 Pylon on pontoon connected to landside by heavy concrete structure.
Pontoon may be additionally stabilised using horizontal cable anchors.

General comments regarding other fjord crossings

Many of the future fjord crossings in Norway will have suspension bridges or similar types of bridges. Site specific conditions will always play an important role.

4.2 Necessary clarifications and further studies

Themes	Actions
Safety	Effect of climatic changes
Road standard etc.	Load requirements Clearance for ships
Studies	Ship impact studies
Studies	Calculations and constructional analysis
Studies	Wind tunnel testing
Studies	Selected areas for full scale testing (Hardanger Bridge)

5. SPECIAL PROBLEMS COMMON TO SEVERAL ALTERNATIVES

5.1 Foundations at extreme water depth

The possibility of placing foundations at very great water depths will be a key factor when designing alternatives for crossing Norwegian fjords. Developing technology for deep water foundations could therefore be a decisive factor for future wide and deep crossings.

Experience from existing bridge foundations and from foundations for oil platforms will be a useful source of information. Reuse of obsolete platform foundations may also of interest.

5.2 Use of horizontal tension anchor cables

Some of the alternatives require use of horizontal anchoring in order to withstand horizontal forces brought about by wind, waves or currents or for other reasons.
These are not well-known technologies, and studies of both materials and methods will be necessary.

5.3 Safety, accidents and excessive load situations

Safety related to normal elements in design follows rules and regulations laid down by national and international standards and is not discussed in these reports.

All known types of accidents, extreme weather situations and possible failures of safety systems have been identified and discussed. This is a special challenge when dealing with new types of structures, which is the situation in crossing the Sognefjord between Lavik and Oppedal.

CONCLUDING REMARKS

The initial seminars brought forward many new alternatives for crossing the very deep and wide Sognefjord.

Further studies by the project group have concluded that a number of the alternatives are realistic, and the project group is continuing this work with the aim of producing documentation as the basis for more detailed development studies.

The results from the seminars and later work by the project group have already been used as a basis for feasibility studies of fjord crossings elsewhere along coastal highway E39.