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Submerged floating tunnels (SFTs) for Norwegian fjords

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Abstract

Submerged floating tunnels (SFTs) weigh roughly the same as the surrounding water. The loads on the tunnel depend on the variation of the forces on the tunnel. The forces come from variation in traffic, current, temperature, waves, weight of water, weight of concrete, growth on the tunnel, wear of asphalt, dust and debris, relaxation of prestress and shrinkage and creep in the concrete. The last six variations are slow and can be counteracted by altering weights in the tunnel.

All structures above sea level are subject to gravity, which tends to limit their spans. In SFTs buoyancy counteracts gravity. This speaks for longer spans, but the slope of roads limit the depth to raise ratio of downward arched SFTs. This tends to limit the free spans. In this article the design of SFTs is discussed. Finally there is a comparison between materials needed for two SFTs and a suspension bridge between Vallavik and Bu in Eidfjord in western Norway. The fjord is ~500 m deep.

It is many years since the author did serious research on submerged tunnels. He has written this contribution in the vain hope that some of his ideas on submerged floating tunnels might be of value to somebody. The author got the idea of SFTs at the technical university in Trondheim from his teacher Erik Ødegård [1]. However the idea is much older. E.J Reed, MP. applied for a patent in 1884. Up to 1968 the following Norwegian names are connected to the idea: Olsen 1923, Sam Lorgen 1968, Sverre Mo 1968.

The author apologizes for not mentioning many other Norwegians who have done valuable work on SFTs. His best publication on submerged tunnels is [2]. It has a list of 32 references.

Keywords: submerged floating tunnels; SFT; Norwegian fjords; suspension bridges; economics; tunneling

1. Introduction

The advantages of the submerged floating tunnels became clear to the author while working on the Limfjord tunnel in Denmark between 1964 to 1968. See Fig. 1.

Here mud was replaced by a layer of sand up to 18m thick. This was to accommodate the load case "water filled tunnel". If this load case had been disregarded, the tunnel could have been founded on the mud. Deformations of the tunnel could have been counteracted by pumping clay in under the tunnel through the tunnel floor [2].

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The Limfjord tunnel has a costly and complicated expansion joint. This joint could have been avoided if the tunnel had been allowed to float freely between the shores. All this would have made the tunnel much less costly.

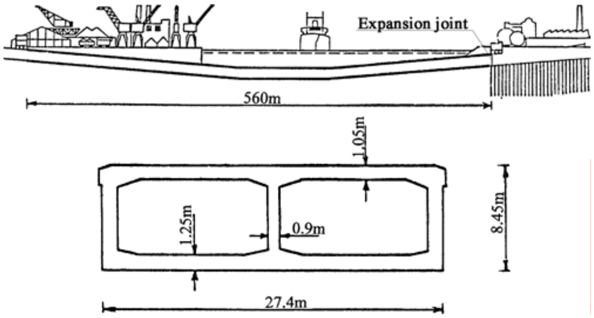

Fig. 1. The Limfjord tunnel [2]

2. Conditions in Norwegian fjords

During ice ages the Norwegian fjords were carved out in solid rock. The strength of the rock is normally best where the fjords are narrowest. Usually the SFT can enter the fjord under the water level through tunnels in solid rock. See Figs. 6 and 7. With a view to building SFTs in Norway, conditions have been examined in Eifjord at Vallavik-Bu [3, 4] and in the Høgsfjord at Oanes [5].

3. Loads on downward arched floating tunnels

Decisions on probable loads are an important part of the design of an SFT as shown in Fig. 2. The traffic is the most important load. See Page 5. The author's work on submerged floating tunnels was carried out when the evenly distributed load per lane was 9kN/m. The max concentrated load was 630kN in each lane. Pedestrians have been disregarded because they will be few and far between. Present-day traffic loads can be counteracted by more prestress. The concrete strength will probably be ample except near the ends of the SFT.

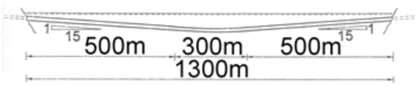

Fig. 2. Downward arched SFT between Vallavik and Bu in Eidfjord in Hardanger in western Norway [2]

Variations in the weight of water will often be the second most important load on an SFT. See Page 5. Near the surface the freshwater moves out of the fjord while heavier salt water moves in below. Wind varying over long periods can influence the movement of the water. Thus the wind can influence the weight of water.

In addition to the factors influencing the weight of the water, the speed of the current is influenced by the tidal currents. Usually the direction of the current is different in the upper and lower parts of the SFT. This reduces the bending due to current. Fig. 4 shows the speed of current assumed by the author.

The ambient water temperature has a great influence on the temperature in the concrete tube. It is fairly constant for most of the SFT. The interior temperature in the tunnel depends on the variation in the outside air and the amount of ventilation. Between Vallavik and Bu 1.5m maximum wave height will give only small stresses in the SFT. See Page 6. That is because the oscillations in the water at 20m under sea level are only about 0.3m. Thus the tendency for stresses due to vibrations in the tunnel is eaten up in the parts of the tunnel that lie more than 20m under sea level. See Fig. 12.

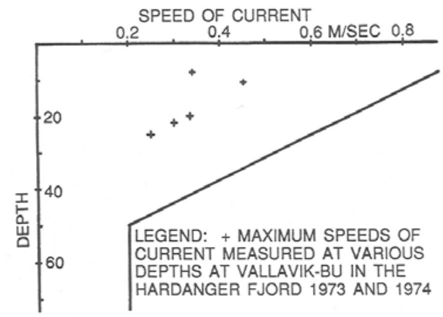

Fig. 3. Assumed variation in the weight of water [6]

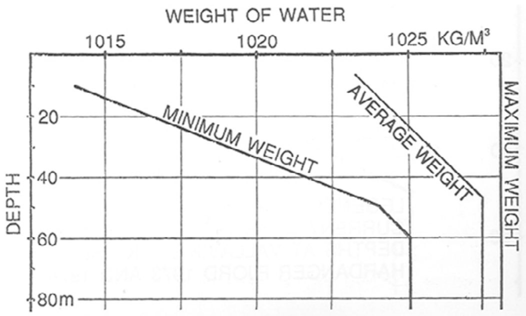

Fig. 4. Assumed speed of current [6]

Loads that change slowly can be counteracted by altering the weight of the tunnel by shifting ballast around. To achieve this, the shape of the tunnel must be checked sufficiently often. This is important for the following loads:

1. The weight of the concrete in the tunnel varies little and changes slowly.
2. Shrinkage and creep of concrete come slowly and tend to shorten the SFT.
3. In the lower part of the SFT there is little growth on the perimeter of the concrete tube.
4. Wear on the asphalt takes place over a long period.
5. Dust and debris in the tunnel are removed periodically.
6. A greater part of the relaxation in the longitudinal prestressing will be over before the tunnel is installed.

4. On the optimal shape of an SFT

The shape of the SFT in Fig. 2 has been chosen for the following reasons: When the vertical curvature is concentrated in the middle of the SFT, it is easier to shorten the concrete tube during installation. When the shape of the SFT is as in Fig. 2, variations in the buoyancy in the middle of the tunnel introduce little bending in the tunnel. Similarly an unusual amount of water in the middle of the tunnel gives little bending and axial force.

5. Production of the concrete tube of an SFT

Fig. 5 indicates how an SFT can be produced. The tunnel is cast on a pontoon. The finished parts of the tunnel are covered by a watertight membrane before they slide into the water. The SFT can have a widening at the lowest point in the tunnel to provide room for temporary parking of cars that have run out of petrol or have stopped for other reasons. The tunnel can also be cast vertically in a slip form. When a cast piece of concrete tunnel is ~100m long, it can be up-ended and joined to a long part of the tunnel [9].

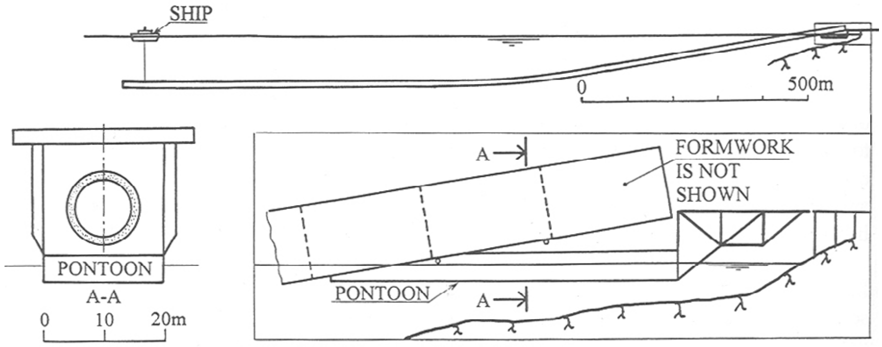

Fig. 5. Pontoon for casting the concrete tube for a downward arched SFT [7, 8]

6. Attaching the concrete tunnel to the shore

Tunnels are blasted through rock at both shores. At the end of the rock tunnel there is a concrete lining with spherical bulkheads and basins for collecting water leaking water. See Figs. 6 and 7. If the shore is steep, the rock from the final blast can slide out into the fjord. See Fig. 6. Before the final blast the rock tunnel is temporarily filled with water at both sides of the spherical bulkhead. This will reduce the shock from the explosion [7].

When the shore is less steep, the rock from the final blast can fall into a collection chamber like shown in Fig. 7 [8]. This is standard practice for the end of a tunnel under a water reservoir in hydroelectric schemes in Norway. After the concrete tube in Fig. 13 is fastened to the end of the lined rock tunnel, the concrete tube can be fastened to the concrete cushion at the far edge of the cavity for collecting the rock from the final blast. See Fig. 7.

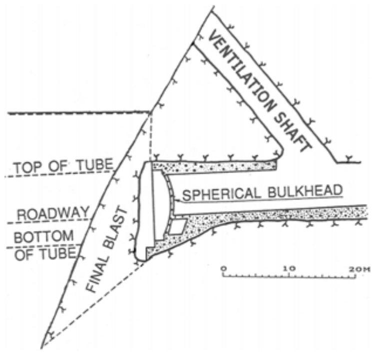

Fig. 6. Abutment in steep rock [6]

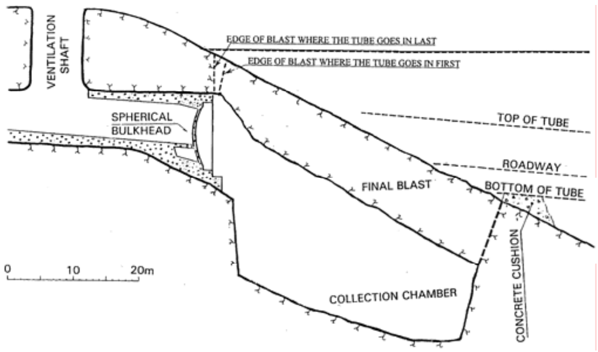

Fig. 7. Approach tunnel in gently sloping rock [5]

7. Moving an SFT into place

Fig. 8 indicates how the concrete tube for the SFT in Fig. 2 can be put in between the abutments. First the concrete tunnel is shortened by concentrating ballast water in the middle of the tunnel. Then the left end of the tube is placed in contact with the rock tunnel on the left shore by tightening steel wires to the shore. When the full length of the Gina touches the abutment, water from between the bulkheads can be let into the rock tunnel. Then the water pressure squeezes the concrete tunnel firmly against the left abutment.

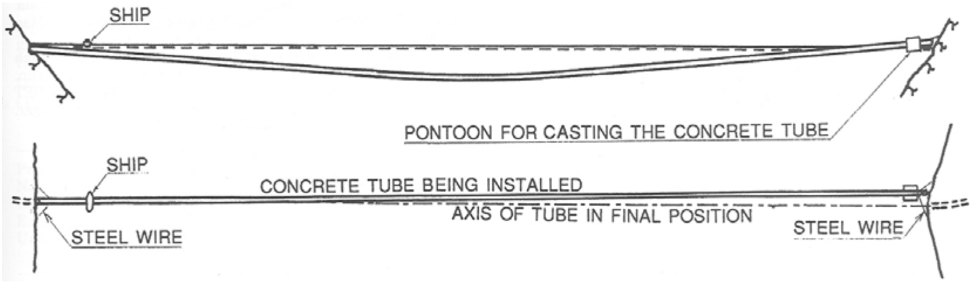

Fig. 8. Starting to put a concrete tube into place between two rock tunnels in a fjord [7]

Now the right end of the tunnel can be put on supports in front of the rock tunnel. See Fig. 6. Then the tunnel can be elongated by removing some of the ballast water in the middle of the tunnel. When the full length of the Gina touches the end of the rock tunnel on the right, then the water between the bulkheads can be removed. Then the tunnel is elongated because the Gina is squeezed towards the right abutment. Then more ballast water can be pumped from the middle of the concrete tunnel. This elongates the tunnel and puts more pressure on the Ginas. Now the bulkheads can be removed and the reinforcement at both ends of the SFT can be put in place and the joints can be cast. Then the rest of the ballast water can be pumped out. Now the SFT is ready for asphalting and technical installation

When to remove the ballast water is an important decision. It influences the stress distribution in the finished concrete tunnel. Exact measurements of the shape of the tunnel are necessary in order to reach good decisions on the ballasting of the tunnel during its lifetime.

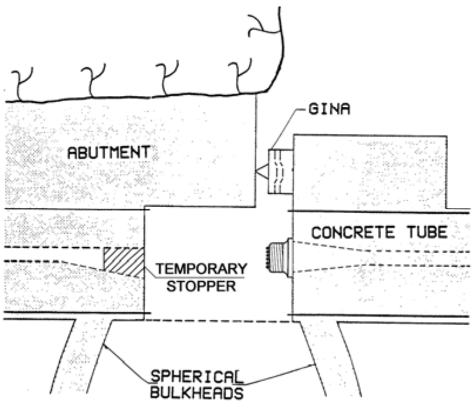

Fig. 9. shows how the edge of the concrete tube meets edge of the rock tunnel [6]

8. Stresses in the SFT between Vallavik and Bu

Stresses in SFTs of the type that that is shown in Fig. 2 have been examined many times [5-7]. The highest stresses occur at the end of the tunnel tube. In the maximum stresses in the serviceability state in a 1250m long SFT was found to be less than $20MN/m^2$. In 80% of the concrete tunnel the maximum stresses were under a third of those at the ends of the concrete tube [5]. See Fig. 10. At the end of the tunnel a lot of reinforcement can be used. Furthermore the gravel can be replaced by concrete at the top and bottom of the cross-section. See Fig. 14.

The bending moments due to current have been found to be around a third of the bending moments due to vertical loads. Thus they are not decisive and horizontal cables to the shores are not necessary. For downward arched concrete tubes with spans over 1700m, it will probably be necessary to increase the diameter of the cross-section at the ends of the tunnel.

The axial force in the tunnel reduces the need for prestress. The axial force should be far from the buckling load. Looking at the horizontal vibrations of the SFT would give due warning if the load in the tunnel is approaching the buckling load. This would occur long before the vibrations represent a nuisance or a danger.

Distance from the end of tube in meters	Maximum tensile stress in upper and lower fiber	Due to traffic load	Due to variation in water density		Due to weight variation Due to marine growth, dirt etc. ± 0.003MN/m	Due to variation in temperature ± 60m	Due to buoyancy	Maximum tensions due to (1) to (6)	Stress due to water pressure	Prestress needed to suppress all tensile stresses
			High	Low						
0	σ_u	15.6	-1.4	4.6	∓ 2.5	± 1.3	-7.5	9.3	-0.3	9.8
	σ_2	3.4	0.9	-3.3	± 1.4	∓ 1.7	+4.8	9.5	-0.5	9.7
125	σ_u	5.4	-0.3	0.9	± 0.8	± 0.7	-2.5	3.0	-0.5	3.2
	σ_2	2.9	-0.2	0.5	∓ 0.3	∓ 1.1	-0.3	2.9	-0.9	2.8
250	σ_u	2.2	0.1	-0.7	± 0.1	± 0.1	1.4	3.3	-0.8	3.2
	σ_2	7.1	-0.6	2.1	∓ 1.2	∓ 0.5	-4.2	3.3	-1.2	2.9
375	σ_u	3.9	0.1	-0.5	± 0.2	± 0.5	+1.0	4.5	-1.1	4.2
	σ_2	8.3	-0.6	1.9	∓ 1.2	∓ 0.2	-3.9	4.4	-1.5	3.7
500	σ_u	5.2	-0.3	0.9	∓ 0.5	∓ 1.1	-1.7	3.8	-1.4	3.2
	σ_2	5.2	-0.2	0.4	∓ 0.5	± 0.8	-1.2	3.8	-1.8	2.8
625	σ_u	6.9	-0.6	1.9	∓ 1.1	± 1.4	-4.1	3.6	-1,5	2.9
	σ_2	2.1	0.1	-0.6	± 0.0	± 1.1	-1.2	3.5	-1.9	2.4
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)

* 0.8 MPa has been added on account of temperature difference in the tube wall.

Fig. 10. Stresses in the serviceability limit state of an SFT with a free span of 1250 (Units MN/m^2) [5]

9. Vibrations due to waves

Fig. 11 shows amplitudes due to sinusoidal deep water waves. At the site of the tunnel in Fig. 2, the characteristic wave height is about 1.6 m [4]. From Fig. 11, it can be seen that the forces due to waves on the SFT in Fig. 7 are substantially reduced because it goes down to 50m below sea level.

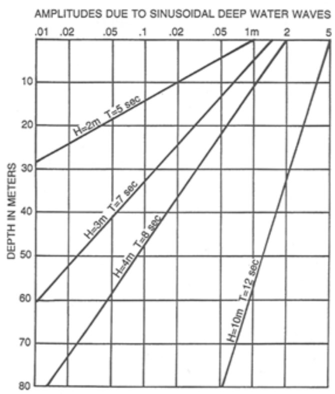

Fig. 11. Oscillations, wave heights H and periods T

This is illustrated by Fig. 12 for a wave height of 1.5m. Such a wave will have a period of around 5sec. One curve shows how maximum amplitude of water particles decreases with increasing distance from the surface. Another curve shows maximum horizontal deflections due to vibrations when the maximum stress in the concrete is 1MPa and the period of vibration is 5sec.

From this we can draw two conclusions:

- Energy absorbed in the upper parts of the SFT will dissipate due to dampening in the lower parts of the SFT.
- Stresses due to wave heights of 1.5m will be less than 1MPa. This is discussed in more detail in [2].

For waves with very long wavelengths, the amplitudes are reduced more slowly with depth. In the sheltered Norwegian fjords waves have small heights. Wave heights of 0.5m seem a likely maximum in many fjords. These waves are very unlikely to give amplitudes that can damage an SFT that can take deflections well over 1.25m.

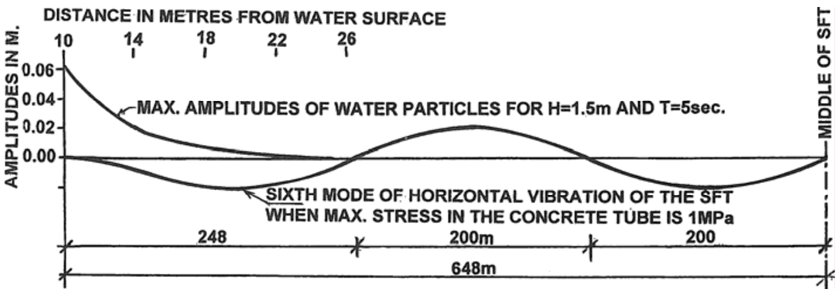

Fig. 12. Comparison of movements of water due to waves and SFT for T = 5 sec [2]

10. Cross-section of concrete tube

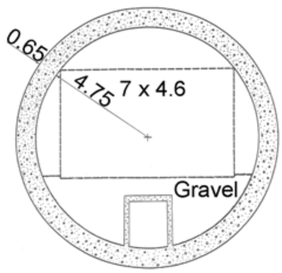

Fig. 13. Cross-section of the SFT in Fig. 2

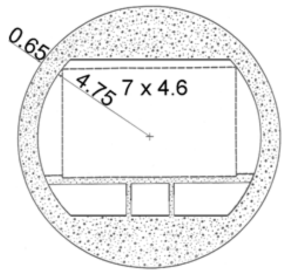

Fig. 14. End cross-section of the SFT in Fig. 2

The cross-section of the concrete tube for the SFT in Fig. 2 can be as shown in Fig. 13. The amount of concrete will be decided mainly by the outer diameter of the tunnel. The buoyancy of the concrete tunnel should give an axial force in the tunnel, but that force should be well below the axial force that can give sideways buckling in the concrete tube. The stresses will be moderate except at the ends of the tunnel. Here the gravel can be replaced by extra concrete at the top and bottom of the cross-section. Prestress and buoyancy are meant to keep the tunnel walls in compression at all times.

11. Water tightness

The outside of the concrete tube has a watertight membrane. Injection should make the rock watertight at both ends of the SFT. Water leaking into the tunnels to the SFT above the sea level should be led into the fjord through tunnels designed for that purpose. At lower levels the water should be pumped out of the SFT. In case of power failure generators should provide the necessary electricity for the pumps. We might want to have generators on both shores. This is important because SFTs filled with water will be lost.

12. Collision with surface vessels and submarines

The highest point on an SFT should be so far from surface that the chance of collision with surface vessels is acceptably low. An SFT being hit by a sinking ship is also very unlikely. The author knows of no investigation of a collision between a submarine and an SFT. To a submarine an SFT is one of very many under water obstacles. Considering the number of obstacles the chance of collision is a strong argument against using drafted personnel in submarines.

13. Comparison between materials needed for two SFTs and a suspension bridge Vallavik-Bu in Eidfjord

In 1979 a very competent committee designed an SFT to cross the Eidfjord from Vallavk to Bu in western Norway [2]. They found that their SFT would cost 19% less than a suspension bridge in the same place. A suspension bridge is now being built at that site. See Fig. 15 and 16.

Information on the suspension bridge has been obtained from the Bridge Section of the Norwegian Public Roads Administration. The suspension bridge is much wider than the SFTs, but in a 6 km long tunnel at the north shore of the suspension bridge the road is ~0.5m narrower than the road SFT in Fig. 2 and in the SFT from 1979. The concrete tubes for the two SFTs have the same inner diameter. A moderate increase in the diameter of the tubes would give a moderate increase in the cost.

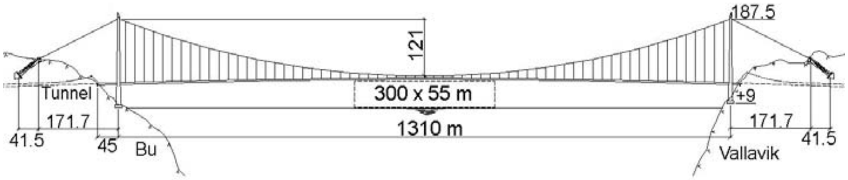

Fig. 15. The suspension bridge that is being built from Vallavik to Bu over the Eidfjord in western Norway

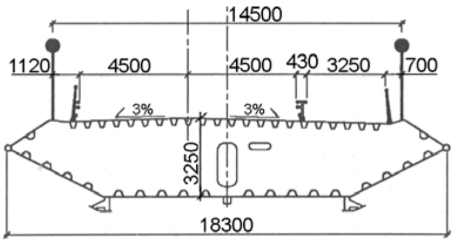

Fig. 16. Cross-section of the bridge in Fig. 15

Table 1 compares materials needed for crossing the Eidfjord at Vallavik-Bu in Hardanger in western Norway. The comparison is flawed for many reasons. The suspension bridge has been designed in great detail. The SFTs have not. The loads for the suspension bridge are up to date. The loads for the SFTs are not. The loads for the suspension bridge are higher than the loads for the SFTs. Higher loads for the SFT in Fig. 2 would lead to more reinforcement and higher utilization of the concrete strength already present in the concrete tube. Maybe there would be a stronger cross-section at the ends of the concrete tunnel. See Fig. 14. Still the comparison indicates that SFTs could be an economic solution for bridging Norwegian fjords over 1000m wide.

Table 1. Materials needed for crossing the Eidfjord at Vallavik-Bu in Hardanger in western Norway

Design alternatives	SFT. 1979	SFT in Fig. 2	Suspension bridge.	Fig. 15 and 16
Concrete in tubes and pontoons	55,240m^3	33,000m^3	22,400m^3	Concrete
Concrete in anchors	6,240m^3	0	0	
Reinforcement	5,745t	2,400t	3,800t	Reinforcement
Prestressing steel	2,175t	1,000t	226t	Prestressing steel
Vertical stays	500t	0	6,400t	Main cables
Horizontal stays	290t	0	8,165t	Structural steel

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