CONCEPTUAL DESIGN OF ESTONIAN LONGEST STRAIT CROSSING

The fixed link between the greatest island of Estonia, Saaremaa and the mainland requires construction of a bridge (or tunnel) from the island Muhu to Saaremaa over the Suur Strait. The island Muhu was connected with the mainland by an embankment, erected more than hundred years ago. The minimum length of the suggested overpass is about 6100 m; it has to have a central channel for navigation (elevation 35 m and width 300 m). By the conceptual design carried out by the author, the overpass consists of a central cable-supported bridge, two approach bridges and embankment sections with a total length of 2850 m. For the navigable part of the overpass various cable-supported structures were under our investigations; a hybrid suspension-cable-stayed structure was preferred. For the approach bridges usual models of composite box girders with spans of 120, 100 and 80 m were chosen.

Для з'єднання найбільшого острова Естонії Сааремаа з материком необхідно спорудити міст (або тунель) з острова Муху на Сааремаа через протоку Суур. Острів Муху з'єднаний з материком насипом, якому більш ніж 100 років. Мінімальна довжина запланованого мостового переходу повинна складати приблизно 6100 м; у нього має бути центральний канал для проходження суден (висота над рівнем моря 35 м та ширина 300 м). За концепцією проекту, розробленого автором, мостовий перехід складається з центрального вантового моста, двох під'їзних мостів та ділянок насипу сумарною довжиною 2850 м. Для судохідної ділянки моста розглядалися різні вантові конструкції; перевага була надана гібридній підвісній конструкції на вантах. Для під'їзних мостів були обрані звичайні конструкції складених балок із коробчастим перерізом з прогонами 120, 100 та 80 м.

Keywords: CAD visualisation, cable-supported structure, discrete analysis, hybrid structure, pre-stressing, self-anchored bridge, suspension bridge.

Ключові слова: візуалізація CAD, вантова конструкція, дискретний аналіз, гібридна конструкція, попереднє напруження, висячий міст із сприйняттям розпору, підвісний міст.

Valdek Kulbach
Dr.Sc. (Eng.), prof.,
Member of Estonian Academy of Sciences,
Tallinn Technical University
Department of Structural Design

1. Introduction

The County of Saaremaa with its territory of 2900 km^2, has about 40,000 inhabitants. Kuressaare, the capital city of Saaremaa, has a population of 16,000. The deepest of Saaremaa harbours on the north-western coast of Saaremaa was constructed in 2006. The deep harbour, ice free all the year round, together with a fixed link to the mainland (Fig.1) would provide Saaremaa with a good transit corridor for transportation of goods and would promote international tourism. In 1996 Saaremaa's newspaper Meie Maa (Our Land) initiated a discussion on the necessity for a bridge. The first article of the author was published in Meie Maa in June 1996. During a year, over 40 articles and comments appeared. Most of the authors supported constructing a bridge. A few preferred building a tunnel or a chain of bridges on the route over Hiiumaa Island.

In March 1997, the Governor of Saare County set up a committee to investigate social, environmental, traffic and technical problems connected with the realization of the project. The activities of the author of this report as a member of the committee were directed to conceptual designing the overpass. In 1998, an Estonian – Finnish working group for drafting a feasibility report concerning the Saaremaa fixed link was formed. The Technical Centre of Estonian Road Administration published the results of the feasibility study in 2000.

Results of surveys conducted with the inhabitants and visitors confirmed 85 % support to the realization of the fixed link. Before announcement of the international competition for the realization of the project based on cost effectiveness, with support of the Estonian Government, some additional geological and environmental investigations and risk analysis are needed.

To determine the location of the bridge, 5 possible traces (Fig. 2) were examined; a number of them were eliminated due to environmental conditions. The shortest of the traces surpasses Suur Strait on the northern coast of the islet of Viire ((trace III). The strait consists of a very shallow western part between the Island Muhu and the islet of Viire and the eastern mainstream channel (Fig. 3).

The geological structure of Suur Strait, whose formation of which has been influenced by various processes already from the Silurian, is very complex. Erection of a bridge implies serious environmental problems. The region of the fixed link is surrounded by natural conservation areas, including a number of nature reserves. Aspects of the biosphere (vegetation, birds, animals, fish), hydrology (sea, ground water) and the atmosphere (air pollution, migration of birds) may be problematic. Environmental impacts will occur during construction as well as the period of the exploitation of the overpass. The depth for the foundation bed of the pylons of the central bridge is about 30 m and maximum depth for foundation bed of the girder bridges in the case of 100 m distance between the bridge piers is about 20 m from the sheet of water. As the thickness of the layer of weak soil is on average 1–2 m, a pile foundation is not very suitable, and a direct foundation should be preferred.

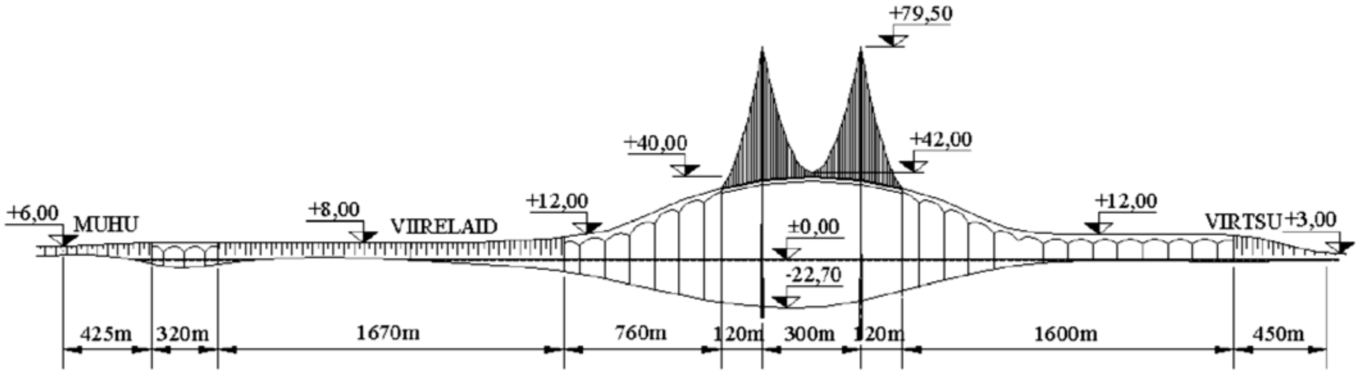

Fig.1. Straits between the Island of Saaremaa and the mainland

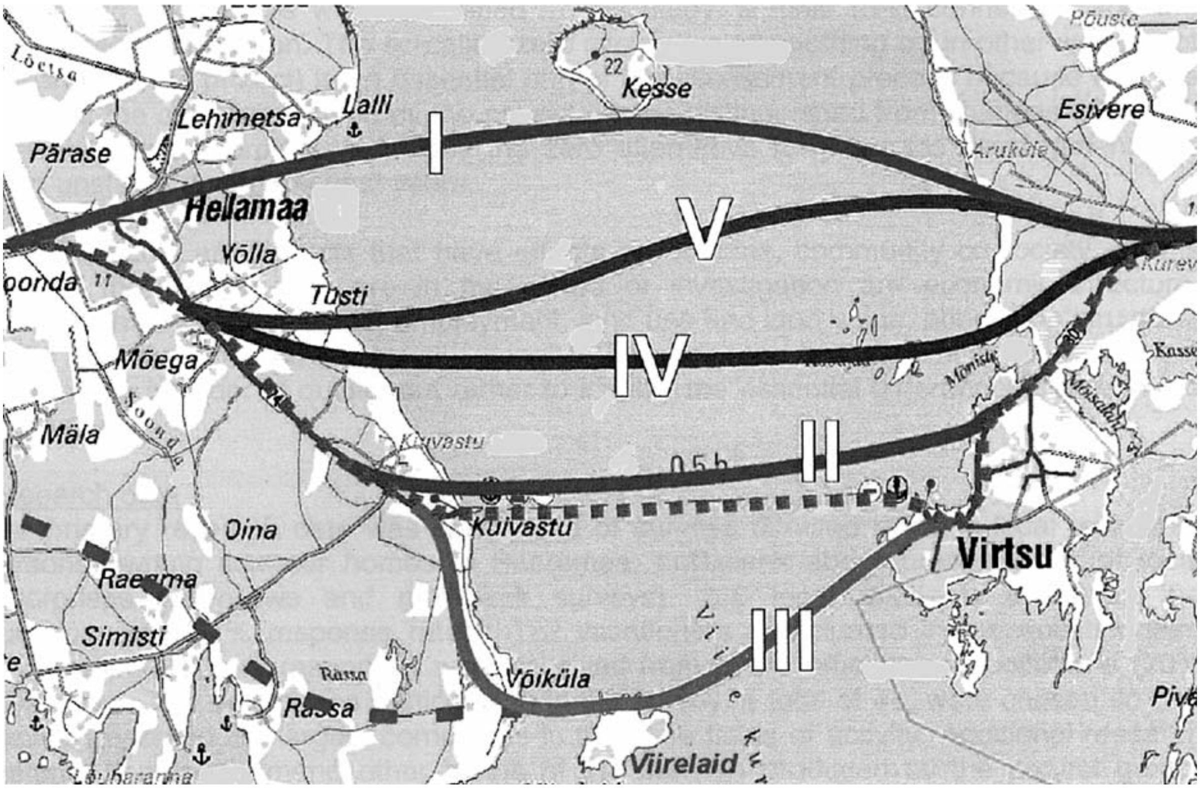

Fig. 2. Possible routes for the Suur Strait crossing

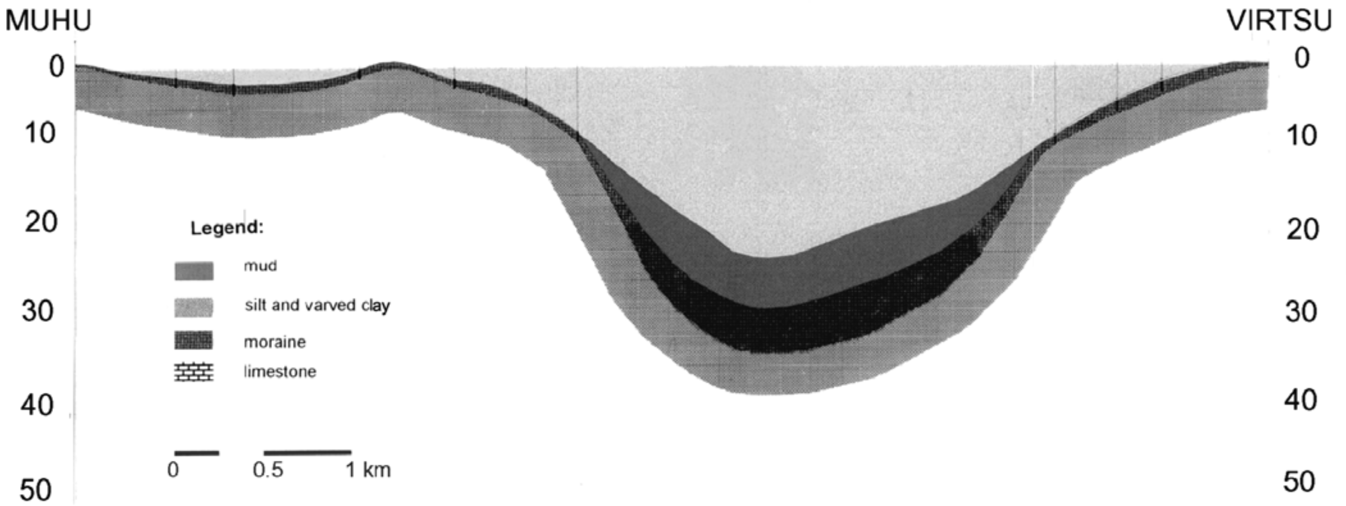

Fig. 3. Cross profile of the Suur Strait

The total width of the bridge deck for the preliminary design was taken 13 m. It corresponds to the second class of bridges, determined by Estonian designing codes. The total width of 13 m consists of the bridge road (two traffic lines of 3,75 m) and two safety trips of 2,75 m; the latter may be used not only as an overpass for pedestrians and cyclists, but also for vehicles forced to stop on the bridge. On two traffic strips, three lines of vehicles may move simultaneously, therefore in the calculations the traffic load from three lines of vehicles was foreseen. Due to the clearance in height of 35 m for the navigable span, the maximum level of the bridge deck was taken +40.00 m from the sheet of water. The longitudinal slope of the bridge deck was chosen based on the condition of fluent transition from the mainland highway to the bridge; the maximum local slope on the transition area was 4 %.

The most important architectural concept of the author for the fixed link comprises a substantial structural separation of the navigable span from the approach bridges [1]. For the navigable part of the overpass, the variants for central span of 300, 400 and 480 m were envisaged. Due to complex estimation of the bridge behaviour under the action of a fluctuating wind load, thorough theoretical analysis and wind-tunnel tests should be carried out before the final design of the bridge; considering serious ice action and possible ship collision, a corresponding risk analysis is also to be done.

2. Suggestions of the author about design of the bridge.

Proceeding from the chosen architectural concept, our main attention was directed to various cable-supported structures for the central part of the overpass. Due to smaller height of pylons we preferred conventional or self-anchored suspension bridges. In the conditions of Saaremaa's overpass, the total price of a conventional suspension structure depends greatly on the main span of the bridge. An increase in the bridge span brings about an increase in the relative cost of the superstructure and a decrease in the cost of the substructure, particularly of the anchor blocks. The depth of the foundation bed is the main factor of the foundation cost. Due to greater depth in the middle part of the strait, conventional bridges with relatively small spans are not suitable for the chosen track. Therefore, the model of a self-anchored structure was preferred. In this case, the stiffening girder is not subjected only to the bending moments, but also to compression forces. Because of very small international experience of design and construction of self-anchored bridges, related theoretical and model test analysis was organized in the Laboratory of Structural Design at TUT. Analysis made was based on a bridge with a span, markedly greater than that in the first stage of design (480 m in comparison with 300 or 400 m). For the given parameters of the bridge, the primary bending moments caused by transversal loads prevail before the secondary moments under the action of eccentricity of axial forces. Both theoretical and experimental analysis on the model 1:100 [2] demonstrated sufficient stability of the girder. On the basis of comparative analysis, a diagram of dependence of the relative cost (reduced to the length unit) of the bridge upon its main span was constructed for a conventional bridge model and for a self-anchored one (Fig 4).

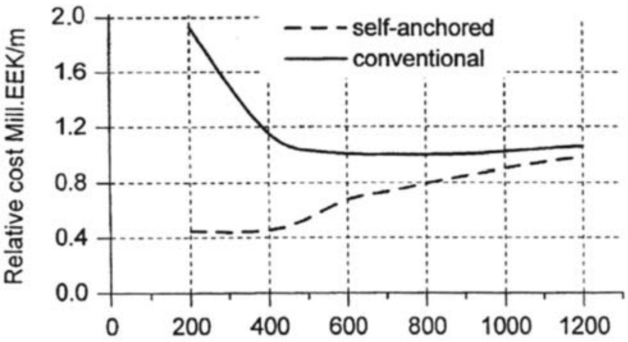

Fig. 4. Comparative cost estimation for conventional and self-anchored suspension bridges

It is noteworthy that with small spans the cost varies greatly and nearly equalizes that of great spans. A view to the central part of the suspension bridge was drafted by means of computer design (Fig 5). In the initial stage of planning, more grandiose dimensions (spans from 600 to 1200 m and even a record value of 2200 m) for the suspension bridge structures were under our investigation. Due to nearly a double cost of a suspension structure per length unit in comparison with girder ones, the chosen span was decreased to the minimum value of 300 or 400 m. For simplification of construction additional stay cables (hybrid structure) may be used.

For approach bridges, frequently box girders are preferred. The span of approach bridges is usually chosen on the basis of minimizing the summary cost of the superstructure and the substructure. Greater spans are more favourable for environmental conditions, than short spans. For a steel superstructure continuous flow-line box girders of constant depth with orthotropic deck plate are common. The East Bridge with the span of 193 m

Fig. 5. means of computer design ????

serves as a good example. The structures mentioned were mounted by floating cranes. Due to very slender girders, special vibration damping equipment was used. Composite structures for continuous girders, as a rule, have variable depth; they consist of steel girders with more developed lower flanges and a reinforced concrete deck plate, cast in situ. As the main option for approach spans of the fixed link of Saaremaa, composite structures of variable depth with spans of 80, 100 and 120 m, depending upon the foundation level, were chosen. Use of the experience of the design and construction of the Great Belt strait crossing is worth mentioning. Problems of the bridge foundation are similar to those for the region of the Great Belt. For the same reasons, the pile foundation was abandoned. Open caisson structures with reinforced bottoms and walls and concrete fillings were chosen

3. Methods used and results of calculation.

Usually the cage of stiffening girders consists of a number of mounting units to be connected after their successive lifting and hanging to the main cables formerly suspended to the pylons. The own weight of the mounting units will be balanced by the cables only. After connecting these units between themselves the composite structure of the cable and the stiffening girder will resist to external loads as a whole. For preliminary design of a suspension bridge continual analysis may be applied [3]. For solution of the corresponding system of nonlinear equations of equilibrium and cables' deformation compatibility an exact method in the form of a complicated transcendental system may be used [4]. Our experience has demonstrated remarkable advantages of an approximate calculation; the approximation as for a single cable in the form of a parabola is not suitable because the derivatives of powers greater than the second are missing in the equations. Therefore it is useful to prescribe the deflection form of the cable by a trigonometric function. Inserting the approximate deflection function into the mentioned equations and applying the method of Galyorkin we obtain for the relative deflection of the structure the following cubic equation

$$\zeta_0^3+\frac{96}{\pi^3}\zeta_0^2+$$
$$+\left[\frac{2048}{\pi^6}+\frac{4E_bI_b(1+\kappa+\vartheta)}{EAf^2}+\frac{8p_0a^4(1+\kappa+\vartheta)}{\pi^2EAf^3}\right]\zeta_0=$$
$$=\frac{256p_1a^4(1+\kappa+\vartheta)}{\pi^5EAf^3}. \tag{3.1}$$

After negligible simplifications the cubic equation (3.1) may be presented in a more compact form

$$\zeta_0^3+3\zeta_0^2+(2+\rho+p_0^*)\zeta_0=p^*, \tag{3.2}$$

where $\rho=\dfrac{4E_bI_b(1+\kappa+\vartheta)}{EAf^2}$ is the relative bending rigidity of the stiffening girder; $p_0^*=H_0/\Phi$; $p^*=P/\Phi$ and $P=pa^2/2f$ are pre-stress and load factors.

For the cable force we have

$$H=H_0+\Phi\zeta_0(2+\zeta_0). \tag{3.3}$$

The maximum value of the bending moment of the stiffening girder

$$\max M=\rho\Phi f\zeta_0. \tag{3.4}$$

For analysis of the bridge under the action of the traffic load, applied on the right half of span it is useful to distribute the load into symmetrical and anti-symmetrical parts. If we denote, as above the initial load by p_0, the additional load over the whole span by p_1 the load on the right half of the span by p_2, the symmetrical part of the additional load will be $p_s = p_1 + 0{,}5p_2$ and the anti-symmetrical part $p_u = 0{,}5p_2$ sgn.x. For the anti-symmetrical load we get an equation for the determination of the displacements parameter w_1 in the form

$$\frac{w_1^3}{f_1^3}+\left[\frac{4E_bI_b(1+\kappa+\vartheta)}{EAf_1^2}+\frac{2(p_0+p_s)a^4(1+\kappa+\vartheta)}{\pi^2EAf_1^3}\right]\frac{w_1}{f_1}=$$
$$=\frac{16p_ua^4(1+\kappa+\vartheta)}{\pi^5EAf_1^3}, \tag{3.5}$$

where in the value of $f_1 = f + w_0$ the displacement under the action of the symmetrical part of the load p_s is to be taken into account.

In the following an example of calculation of displacements and inner forces for a pedestrian bridge is treated. Let us have a suspension bridge with the following parameters: 1) the middle span $l = 2a = 45$ m; 2) the sag of the cable $f = 6$ m; 3) the side spans $b = 15$ m, $tg\,\beta = 0{,}45$; 4) the rigidity parameters of the stiffening girder (I 60): $E = 0{,}21 \cdot 10^6$ MPa, $I = 75010$ cm^4, $EI = 148{,}1$ MN m^2; 5) the rigidity parameters of the cables (∅ 52): $E = E_a = 0{,}16 \cdot 10^6$ MPa, $A = A_a = 10{,}6$ cm^2, $EA = E_aA_a = 313{,}6$ MN; 6) the loads of the bridge: $p_0 = 2{,}0$ kN/m – the initial load (weight of stiffening girders), $p_1 = 2{,}0$ kN/m – the dead load, $p_2 = 10{,}0$ kN/m – the live load.

Table 3.1. Comparison of deflections and inner forces calculated by exact and approximate analysis

Para-Meter	x / a	Total loading			Combined loading		
		Exact	Apr.1	Apr. 2	Exact	Apr.1	Apr. 2
w (m)	–0,5	0,132	0,132	0,125	0,019	0,017	–0,012
	0	0,181	0,186	0,177	0,107	0,110	0,105
	+0.5	0,132	0,132	0,125	0,171	0,172	0,160
H (kN)	–	551	550	550	360	367	365
M (kNm)	–0,5	106	101	104	–220	–231	–207
	0	136	143	147	124	85	57
	+0,5	106	101	104	342	351	321

For analysis an exact calculation was made from one side and calculation by means of approximate formula (3.1) – Apr. 1 and formula (3.2) – Apr. 2 from the other side. Corresponding results of calculation are given in Table 3.1. Comparison of the results of calculation demonstrates a fair accordance in values of displacements of the structure and cable forces; approximate bending moments of the girder differ from the exact values by about 5 %.

For options of cable-stayed and hybrid structures and also for cases of loading a suspension bridge by concentrated forces, use of discrete calculation models is unavoidable [5]. Discussion, conclusions and recommendations.

1. Realization of a fixed link to Saaremaa, a largest structure in Estonia, is a challenging task for Estonian bridge designers and scientists [6]. Due to the specificity of strait bridges and high capacity of construction work, teamwork of engineers, scientists and construction enterprises of other countries is inevitable. First steps towards collaboration with authorities and specialists of Finland, Norway and Denmark have already been taken.

2. Economically, the most suitable bridge track for the fixed link to Saaremaa is the southern track passing over the northern top of the Islet of Viire.

3. Due to greater visual attraction of the navigable span, the central part of the overpass in the form of a cable-stayed bridge or a self-anchored suspension structure is to be preferred. In spite of any advances of long-span girder structures for shorter overpasses, the visual impression of a long overpass with a similar structure of the central span and approach bridges seems to be monotonous and misleading for navigation.

4. Analysis of the behaviour of a self-anchored structure demonstrated sufficient stability of its stiffening girder, in spite of its very small stiffness in bending. In real conditions the model with straight anchor cables has substantial advantages over the model with loaded ones.

5. The total cost of the overpass with the central span in the form of a bowstring arch, cable-stayed model or self-anchored suspension structure (including the hybrid structure) varies only within 2–3 %. In all these cases the total cost remains within 1,8–2,0 milliard EEK. The structural model for the central span is to be chosen on the basis of architectural considerations between options presented in previous sections. It should also be mentioned that the model of the cable-stayed bridge is characterized by much higher pylons than the other options.

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