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Determination of structural behavior of Bosporus suspension bridge considering construction stages and different soil conditions

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Abstract. In this paper, it is aimed to determine the structural behavior of suspension bridges considering construction stages and different soil conditions. Bosporus Suspension Bridge connecting the Europe and Asia in Istanbul is selected as an example. Finite element model of the bridge is constituted using SAP2000 program considering existing drawings. Geometric nonlinearities are taken into consideration in the analysis using P-Delta large displacement criterion. The time dependent material strength of steel and concrete and geometric variations is included in the analysis. Time dependent material properties are considered as compressive strength, aging, shrinkage and creep for concrete, and relaxation for steel. To emphases the soil condition effect on the structural behavior of suspension bridges, each of hard, medium and soft soils are considered in the analysis. The structural behavior of the bridge at different construction stages and different soil conditions has been examined. Two different finite element analyses with and without construction stages are carried out and results are compared with each other. At the end of the analyses, variation of the displacement and internal forces such as bending moment, axial forces and shear forces for bridge deck and towers are given in detail. Also, displacement and stresses for bridge foundation are given with detail. It can be seen from the analyses that there are some differences between both analyses (with and without construction stages) and the results obtained from the construction stages are bigger. It can be stated that the analysis without construction stages cannot give the reliable solutions. In addition, soil condition have effect on the structural behavior of the bridge. So, it is thought that construction stage analysis using time dependent material properties, geometric nonlinearity and soil conditions effects should be considered in order to obtain more realistic structural behavior of suspension bridges.

Keywords: construction stage analysis; Bosporus suspension bridge; finite element analysis; soil condition effect; time dependent material properties

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1. Introduction

In recent years, the construction of suspension bridges has increased. Because they are built for both crossing the long span (> 550 m) and giving the rise to the usage of domains under the bridge. Suspension bridges are very important engineering structure due to the high costs and logistical importance. So, the analysis of suspension bridges must be done on the best possible analytical model since structural elements such as deck, towers and cables show different structural behaviour.

Finite element analysis is the most important engineering method in order to obtain the behavior of the structures under variable loads. This method is widely used to determine the static and dynamic behavior of the engineering structures. But, in the analytical solutions based on finite element models, it is assumed that the structure is built and loaded in a second. However, this type of analysis does not always give the reliable and healthy solutions. Because, construction period of the engineering structures such as suspension bridges, highway and cable-stayed bridges continue along time and loads may be change during this period. Therefore, construction stages and time dependent material properties should be considered in the analysis to obtain the reliable results.

In the literature, some papers exist about the construction stage analysis of the long span bridges considering time dependent material properties. Ko *et al*. (1998) calculated the dynamic characteristics such as natural frequencies and mode shapes of suspension deck in construction stages. The Tsing Ma suspension bridge with a main span of 1377 m and an overall length of 2160 m is performed. Kwak and Seo (2002) determined the time dependent behaviour of precast prestressed concrete girder bridge. To analyze the long-term behaviour of bridges, the effects of creep, the shrinkage of concrete, and the cracking of concrete slabs in the moment regions is considered. Cheng *et al*. (2003) carried out the wind induced load capacity of a long span steel arch bridge during two construction stages. The Lupu Bridge which has 550 m central span length and 100 m side spans is selected as a case study. Wang *et al*. (2004) analyzed a cable stayed bridge during construction using the cantilever method. Two computational processes, one is a forward process analysis and the other is a backward process analysis are established. Pindado *et al*. (2005) investigated the influence of the section shape of box girder decks on the moments during construction stages experimentally. Karakaplan *et al*. (2007) performed the construction stage analysis of a cable supported pedestrian bridge considering time dependent material strength variations. Analysis results are compared with the conventional finite element analysis and the differences are determined. Cho and Kim (2008) carried out probabilistic risk assessment for the construction stages of the Hanbit suspension bridge. The bridge is under construction and will be one of the longest suspension bridges in Korea in 2010. The main span is designed to be 850 m with two side spans of 255 and 220 m each. Tensile forces for main cables and deflections for stiffening girders are controlled for each construction stages. Somja and Goyet (2008) studied about nonlinear finite element analysis of segmentally constructed cable stayed bridge. Time dependent effects including load history, creep, shrinkage and aging of the concrete are considered in the analyses. Modification of the bridge topology has been carried out using an efficient procedure for creating/removing elements. Altunışık *et al*. (2010) performed the construction stage analysis of Kömürhan Highway Bridge. The bridge is a reinforced concrete box girder bridge and constructed with balanced cantilever method, located on the 51st km of Elazığ-Malatya highway. Adanur and Günaydın (2010) studied about construction stage analysis of Bosporus suspension bridge. Bosporus Suspension Bridge connecting the Europe and Asia in Istanbul is selected as an example. Two different finite element analyses with and without construction stages are carried out and results are compared with each other. Ateş (2010) studied about analytical modelling of continuous concrete box girder bridges considering construction stages. Budan Bridge is selected as a numerical example. The Bridge constructed with balanced cantilever method and located on Artvin-Erzurum highway, Turkey, at 55+729-56+079.000 km. The structural behaviour of the bridge at different construction stages has been examined. Variation of internal forces such as bending moment, shear forces and axial forces, and displacements for bridge deck and pier are given in detail. Soyluk *et al*. (2010) carried out time dependent nonlinear analysis of segmentally erected cable-stayed bridges. The analysis phase is divided into two phases: The construction phase and the service phase. In the analyses, while 33 stages which cover 970 days are considered for the construction phase, 3 stages which lasts up to 10 years are used for the service phase. The analytical models of the selected numerical example are solved by considering the self weight and the time-dependent nonlinear effects. The bridge responses are then compared with respect to the time-dependent effects. The results of the study show that time-dependent effects can have important effects on cable-stayed bridges. Brownjohn *et al*. (2010) carried out ambient vibration re-testing and operational modal analysis of the Humber Bridge. The paper describes the equipment and procedures used for the exercise, compares the operational modal analysis technology used for system identification and present modal parameters for key vibration modes of the complete structure. Adanur *et al*. (2012) and Gunaydin *et al*. (2012) studied about analytical modelling of Humber and Fatih Sultan Mehmet Suspension bridge considering construction stages. Ateş *et al*. (2013) worked on effects of soil-structure interaction on construction stage analysis of highway bridges. In the study, two different finite element analyses, with and without construction stage, carried out on Kömurhan Bridge between Elazig and Malatya province of Turkey, over Firat River.

As seen in literature, there is not sufficient research about the construction stage analysis of suspension bridges. To this end, this paper presents construction stage analysis of suspension bridges using time dependent material properties and different soil conditions. Time dependent material properties are considered as compressive strength, shrinkage, creep and aging for concrete, and relaxation for steel.

2. Description of Bosporus suspension bridge

The Bosporus suspension bridge (Fig. 1) connecting the Europe and Asia Continents in Istanbul, Turkey is a 1560 m long with a main span of 1074 m and side spans of 231 m and 255 m on the European and the Asian sides respectively, without any side spans supported by cables. Construction of the bridge started in 1973 and completed in 1983. The decks of the side spans at the bridge are supported on the ground by piers. The bridge has flexible steel towers of 165 m high, inclined hangers and a steel box-deck. The horizontal distance between the cables is 28 m and the roadway is 21 m wide, accommodating three lanes each way.

The roadway at the mid-span of the bridge is approximately 64 m above the sea level. Schematic representation of Bosporus Suspension Bridge including dimension is given in Fig. 2.

The deck was constituted considering aerodynamic form to reduce of the wind affect along the bridge deck. The aerodynamic steel box girder deck (Fig. 3) of the bridge consist of 60 box girder deck pieces of 17.9 m long 3 m deep prefabricated sections 33 m wide. The top of each box section constitutes an orthotropic plate on which 35 mm thickness mastic asphalt surfacing is laid.

Fig. 1 Bosporus suspension bridge

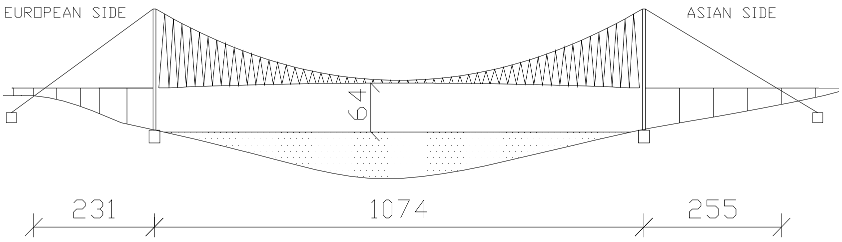


Fig. 2 Schematic representation including dimension (dimensions as m)

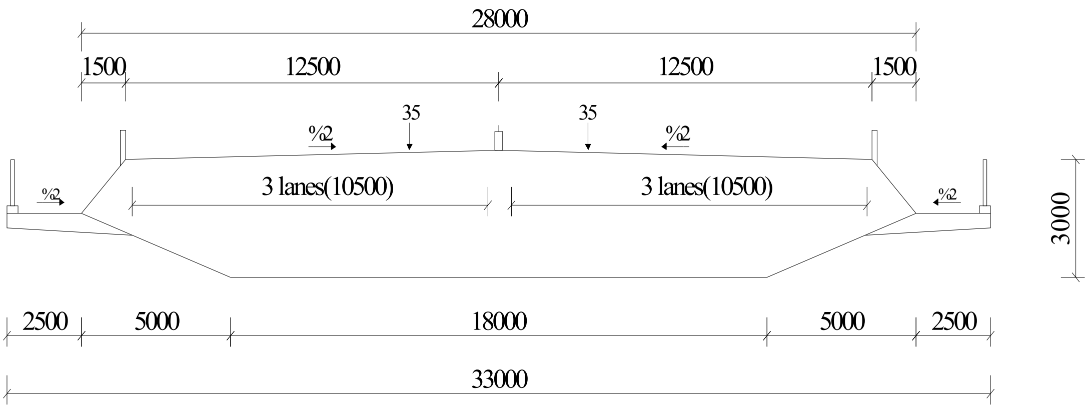


Fig. 3 Dimensions of aerodynamic steel box girder deck (dimensions as mm)

The bridge has slender steel towers of 165m high. The tower legs are 5.20 × 7.00 m at the bottom and they become 3.00 × 7.00 m at the top. Vertical tower legs are connected by tree horizontal portal beams. Dimension of towers are given in Fig. 4.

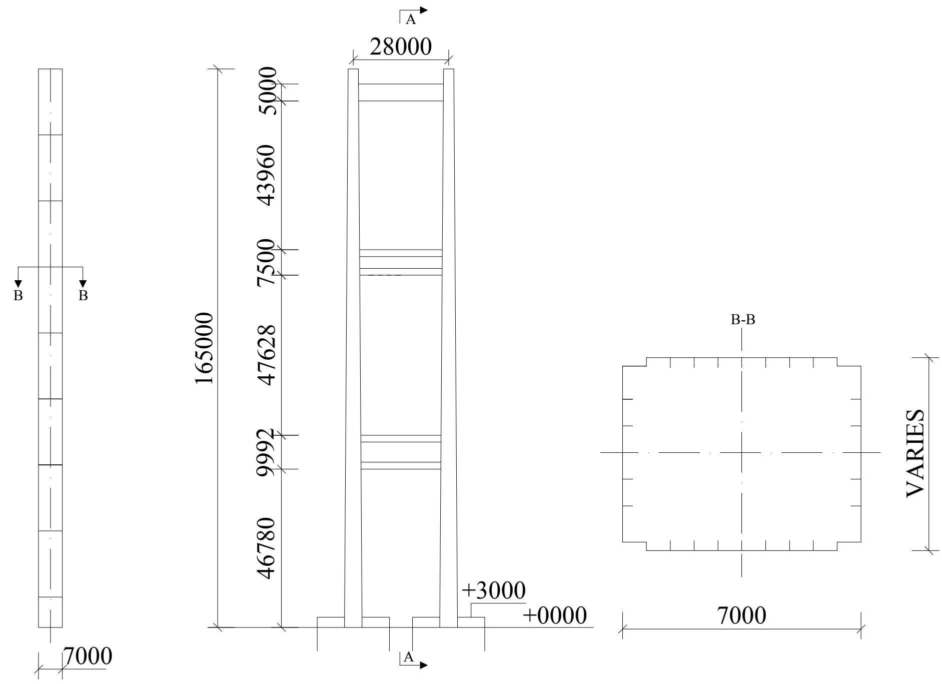


Fig. 4 Dimensions of towers (dimensions as mm)

Main cables of the bridge are built up parallel wire, 5 mm in diameter over the hot dipped galvanizing. Each main cable consists of 19 strands extending between towers and contains 548 parallel wires, with other four stands each of which contains 192 wires in the backstays.

3. Finite element analysis

Finite element analyses are commonly considered in the design and project phase of the important engineering structures such as bridges using some special software. In this study, SAP2000 finite element program (SAP2000 2008) which is used for linear and non-linear, static and dynamic analyses of 3D models of structures is used in the analysis. To investigate the construction stage response of the Bosporus Suspension Bridge, two-dimensional finite element model are used for calculations. To determine of structural behavior of suspension bridges considering different soil conditions four finite element model is constituted. In the finite element model, the cross section of the foundation is considered as 15×19 m and 8 m height. The soil-structure interaction of the bridge is represented by spring elements assigned to the foundation on which the towers are seated. The soil properties used in the finite element models are given in Table 1.

- Model 1: Soil-structure interaction is not taken into consideration in the analysis. The fixed support is considered as the support condition on the bridge towers.
- Model 2: Soil-structure interaction is taken into consideration in the analysis. The soil condition is considered as hard soil.

Table 1 Properties of the soil types

Finite element model	Soil type	Spring type	Coefficient of subgrade (kN/m^3)
1	Hard	Simple	100.000
2	Medium	Simple	50.000
3	Soft	Simple	20.000

Table 2 Material and section properties of the element of Bosporus Bridge

Element	Material Properties			
	Modulus of elasticity	Poisson's ratio	Section areas	Inertia moment
	kN/m^2	-	m^2	m^4
Towers	2.05E8	0.30	1.360	9.0000
Deck	2.05E8	0.30	0.851	1.2380
Main cable	1.93E8	0.30	0.410	0.0133
Side span cable	1.93E8	0.30	0.438	0.0153
Hanger	1.62E8	0.30	0.0042	-

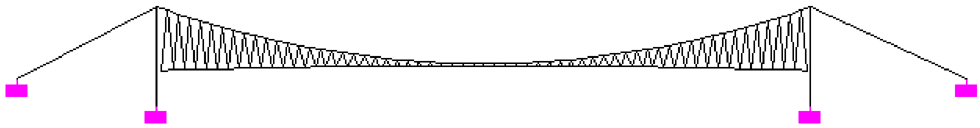
- Model 3: Soil-structure interaction is taken into consideration in the analysis. The soil condition is considered as medium soil.
- Model 4: Soil-structure interaction is taken into consideration in the analysis. The soil condition is considered as soft soil.

The finite element models of Bosporus Suspension Bridge are shown in Fig. 5. As the deck, towers and cables are represented by beam elements, the hangers are represented by truss elements in the model. The finite element model of the bridge with 202 nodal points, 199 beam elements and 118 truss elements are considered for the analyses. The selected finite element model of the bridge is represented by 475 degrees of freedom (Fig. 5). The material and section properties of the element used in the finite element model are given in Table 2. In the analyses of the bridge, the following load cases are considered.

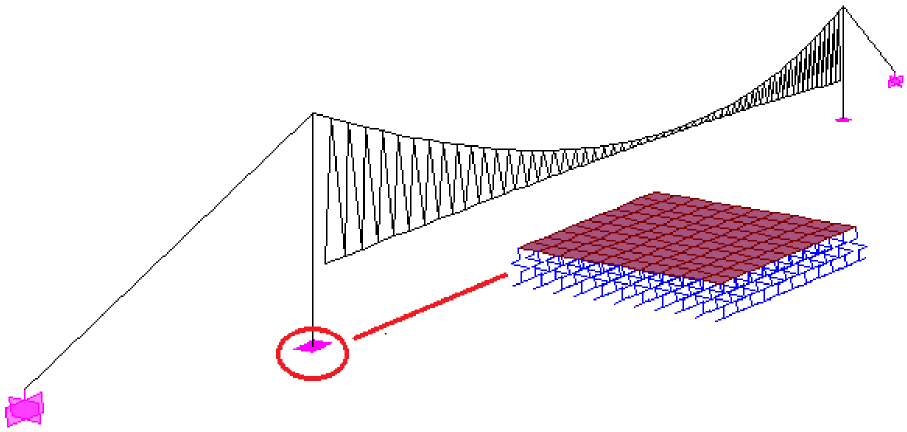
- Dead load: Weight of all elements. They are calculated from the finite element software directly.
- Additional mass: Weight of the asphalt, cobble, pipeline and its supports, scarecrow. 40 kN/m distributed load is added to each segment.

4. Modelling of the construction stages

In the construction stage analyses of Bosporus Suspension Bridge, a total of 31 construction stages are considered. Total duration from the beginning to ending of construction is considered as 800 days not considering soil conditions. Total duration from the beginning to end of construction is considered as 950 days when the soil conditions are considered. Maximum total step and maximum iteration for each step are selected as 200 and 100, respectively. Some construction



(a) Without soil conditions



(b) With soil conditions

Fig. 5 Two-dimensional finite element models of Bosporus suspension bridge

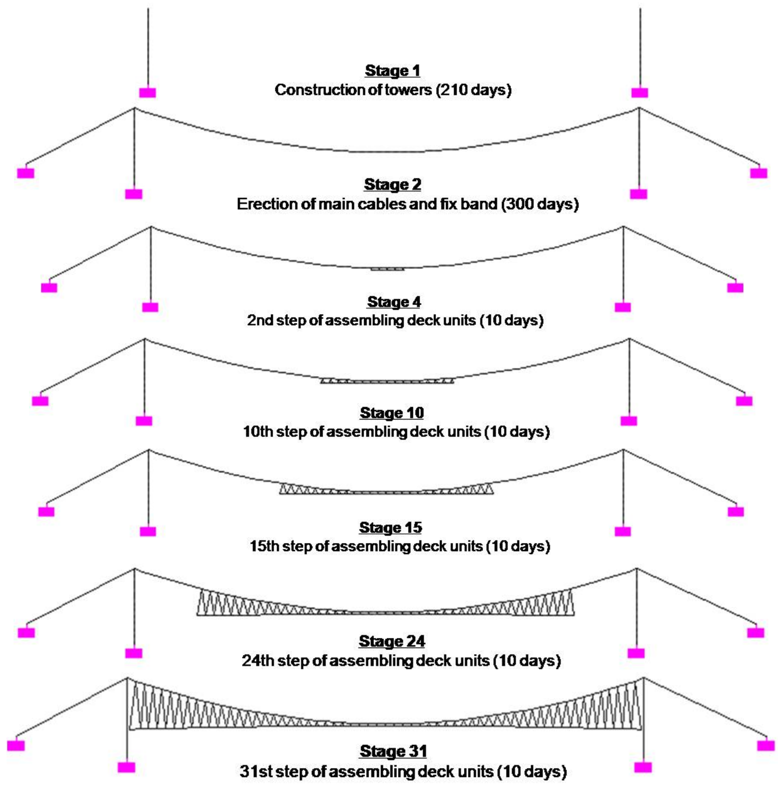


Fig. 6 Some construction stages not considering soil conditions of Bosporus suspension bridge

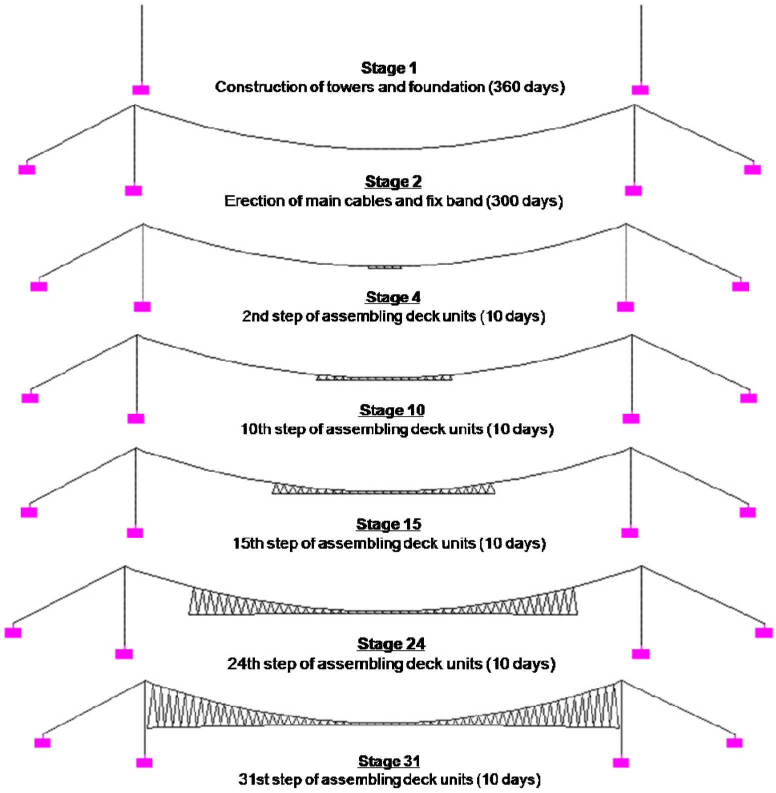


Fig. 7 Some construction stages considering soil conditions of Bosporus suspension bridge

stages not considering soil conditions and considering soil conditions using SAP2000 finite element analysis program are shown in Figs. 6 and 7 respectively.

In the construction stage analysis, some special points given in below should be considered:

- Geometric nonlinearities should be taken into consideration in the analysis using P-Delta large displacement criterion,
- All construction stages and their details should be determined from design to opening the traffic of the bridge,
- Working plan including construction durations of main structural elements (tower, deck and cable) of the bridge should be prepared,
- Added and removed loads for each construction stages should be determined,
- To obtain the reliable solution, each stage results should be added to end of the each stage and next stage analysis is done,
- Non-linear solution parameters should be selected depending on the literature.

5. Time dependent material properties

In the construction stage analysis of bridges, time dependent material properties such as elasticity modulus, creep and shrinkage for concrete and relaxation for the prestressed steel should be considered, because they are variable due to the climate during construction (Altunışık 2010, Altunışık *et al*. 2010). For example, strength of the concrete increase continuously at 7^{th}, 28^{th} and 1000^{th} days of concreting. If these properties are not considered in the analysis, analysis of the bridges may not give the reliable results. Time effects and cracking make analysis even more complex for bridges. Creep strains develop at early stages of the construction process and continue to evolve significantly after the structure is built. Depending on the construction method, restrained creep can appear and induce important stress redistribution in the structure (Somja and Goyet 2008). To accurately analyze structures both during their construction and along their entire life, engineers must have at their disposal appropriate design methods. The effects of geometry changes occurring during construction of the structure cannot be taken into account using standard finite element codes since structural elements are added and removed at certain time instants (Somja and Goyet 2008).

The iterative calculations at each construction stage considering added stiffness from the initial equilibrium state. The matrix form of finite element method is given the following equation

$$\{F\} = [K]\{U\} \tag{4.1}$$

where $[K]$ is the stiffness matrix including elastic stiffness matrix and geometric stiffness matrix. The finite element analysis is performed at each construction stages of the bridge by using SAP2000.

5.1 Compressive strength

The compressive strength of concrete at an age t depends on the type of cement, temperature and curing conditions. The relative compressive strength of concrete at various ages may be estimated by the following formula (CEB-FIP 1990).

$$f_{cm}(t) = \beta_{cc}(t) f_{cm} \tag{4.2}$$

in which $\beta_{cc}(t)$ is a coefficient with depends on the age of concrete and is calculated by

$$\beta_{cc}(t) = \exp\left\{ s \left[1 - \left(\frac{28}{t/t_1} \right)^{1/2} \right] \right\} \tag{4.3}$$

$f_{cm}(t)$ is the mean concrete compressive strength at an age of t days, f_{cm} is the mean compressive strength after 28 days, t is the age of concrete in days and s is a cement type coefficient.

5.2 Aging of concrete

The modulus of elasticity of concrete changes with time. For this reason, the modulus at an age $t \neq 28$ days may be estimated as below equation

$$E_{ci}(t) = E_{ci}\sqrt{\beta_{cc}(t)} \tag{4.4}$$

where $E_{ci}(t)$ is the modulus of elasticity at age of t days, E_{ci} is the modulus of elasticity at an age of 28 days, $\beta_{cc}(t)$ is a coefficient which depends on the age of concrete.

5.3 Shrinkage of concrete

The CEB-FIP Model Code gives the following equation of total shrinkage strain of concrete

$$\varepsilon_{cs}(t,t_s) = \varepsilon_{cso}\beta_s(t-t_s) \tag{4.5}$$

where ε_{cso} is notional shrinkage coefficient, β_s is the coefficient to describe the development of shrinkage with time, t is the age of concrete in days and t_s is the age of concrete in days at the beginning of shrinkage. The notional shrinkage coefficient may be obtained from

$$\varepsilon_{cso} = \varepsilon_s(f_{cm})\beta_{RH} \tag{4.5.a}$$

$$\varepsilon_s(f_{cm}) = \left[160 + 10\beta_{sc}\left(9 - \frac{f_{cm}}{f_{cmo}}\right)\right] \tag{4.5.b}$$

where f_{cm} is the mean compressive strength of concrete at the age of 28 days in MPa; f_{cmo} is taken as 10MPa; β_{sc} is a coefficient ranging from 4 to 8 which depends on the type of cement.

$$\begin{aligned} \beta_{RH} &= -1.55\beta_{sRH} \quad && 40\% \le RH < 90\% \\ \beta_{RH} &= 0.25 && RH \ge 99\% \end{aligned} \tag{4.6}$$

where

$$\beta_{sRH} = 1 - \left(\frac{RH}{RH_o}\right)^3 \tag{4.7}$$

with RH is the relative humidity of the ambient atmosphere (%) and RH_o is 100%. The development of shrinkage with time is given by

$$\beta_s(t-t_s) = \sqrt{\frac{(t-t_s)/t_1}{350(h/h_o) + (t-t_s)/t_1}} \tag{4.8}$$

where h is the notional size of member (mm) and is calculated by $h = 2A_c / U$ in which A_c is the cross-section and u is the perimeter of the member in contact with the atmosphere; h_o = 100 mm and t_1 = 1 day.

5.4 Creep

The effect is calculated using CEB-FIP Model Code (1990) creep model. For a constant stress applied at time t_o, this leads to

$$\varepsilon_{cc}(t,t_0) = \frac{\sigma_c(t_o)}{E_{ci}}\phi(t,t_0) \tag{4.9}$$

in which $\sigma_c(t_o)$ is the stress at an age of loading t_o, $\phi(t, t_o)$ is the creep coefficient and is calculated from

$$\phi(t, t_0) = \beta_c(t - t_0)\phi_o \tag{4.10}$$

where β_c is the coefficient to describe the development of creep with time after loading, t is the age of concrete in days at the moment considered, to is the age of concrete at loading in days. The creep coefficient is explained by

$$\phi_o = \phi_{RH}\beta(f_{cm})\beta(t_o) \tag{4.11.a}$$

$$\phi_{RH} = 1 + \frac{1 - \left(\dfrac{RH}{RH_0}\right)}{0.46\left(\dfrac{h}{h_o}\right)^{1/3}} \tag{4.11.b}$$

$$\beta(f_{cm}) = \frac{5.3}{\sqrt{\dfrac{f_{cm}}{f_{cmo}}}} \tag{4.11.c}$$

$$\beta(t_o) = \frac{1}{0.1 + \left(\dfrac{t_o}{t_1}\right)^{0.2}} \tag{4.11.d}$$

All parameter is defined above. The development of creep with time is given by

$$\beta_c(t - t_o) = \left[\frac{(t - t_o)/t_1}{\beta_H + (t - t_o)/t_1}\right] \tag{4.12.a}$$

$$\beta_H = 150\left\{1 + \left(1.2\frac{RH}{RH_o}\right)^{18}\right\}\frac{h}{h_o} + 250 \leq 1500 \tag{4.12.b}$$

where t_1 = 1 day; RH_o = 100 and h_o = 100 mm.

5.5 Relaxation of steel

According to CEB-FIP Model Code (1990), relaxation classes referring to the relaxation at 1000 hours are divided into three groups for prestressing steels. The first relaxation class is defined as the normal relaxation characteristics for wires and strands, the second class is defined as improved relaxation characteristics for wires and strands, and the last one is defined as relaxation characteristics for bars.

For an estimate of relaxation up to 30 years the following formula may be applied

$$\rho_t = \rho_{1000}\left(\frac{t}{1000}\right)^k \tag{13}$$

where ρ_t is the relaxation after t hours; ρ_{1000} is the relaxation after 1000 hours; $k \approx \log(\rho_{1000}/\rho_{100})$ in which k to be 0.12 for relaxation class1, and 0.19 relaxation class2; ρ_{100} is the relaxation after 100 hours. Normally, the long-term values of the relaxation are taken from long-term tests. However, it may be assumed that the relaxation after 50 years and more is three times the relaxation after 1000 hours.

Selected analysis parameters to consider time dependent material properties are given in Table 3.

Table 3 Selection of analysis parameters to consider time dependent material properties in SAP2000

Parameters		Main structural elements		
		Deck	Tower	Foundation
Material properties		Steel Isotropic	Concrete Isotropic	Concrete Isotropic
Nonlinear material data	Hysteresis type	Kinematic	Kinematic	Kinematic
	Stress-strain diagram	User defined	User defined	User defined
Time dependent properties	Elasticity modulus	-	✓	✓
	Creep	-	✓	✓
	Shrinkage	-	✓	✓
	Creep analysis type	-	-	✓
	Cement type coefficient	-	-	0.25
	Relative humidity %	-	-	60
	Notional size		-	2.05
	Shrinkage coefficient			5
	Shrinkage start age	0	0	0
	Steel relaxation	✓	✓	-
	Relaxation analysis type	Full	Full	-
	CEB-FIP class	1	1	1

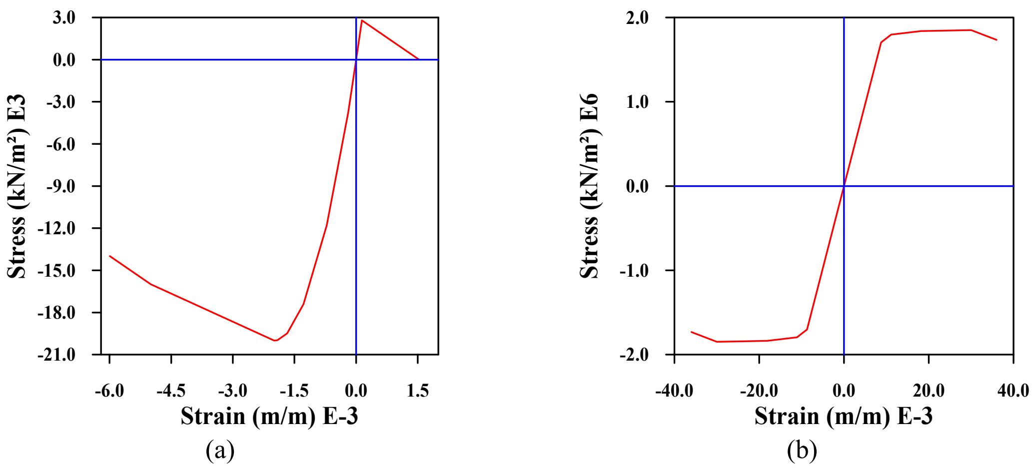
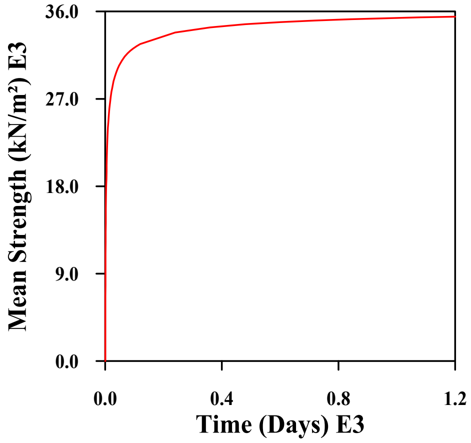
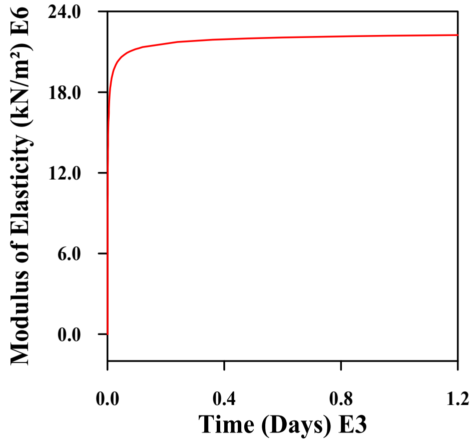


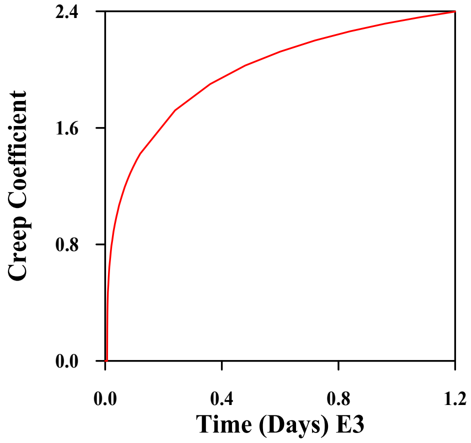
Fig. 8 Stress-strain diagrams used for (a) concrete; and (b) prestressed steel



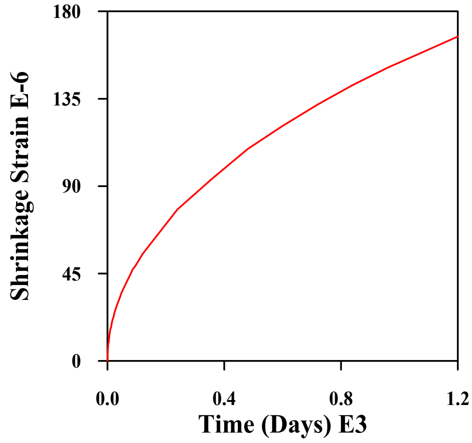
(a) Time dependent mean strength



(b) Time dependent modulus of elasticity



(c) Time dependent creep coefficient



(d) Time dependent shrinkage strain

Fig. 9 Variation of time dependent material properties for concrete

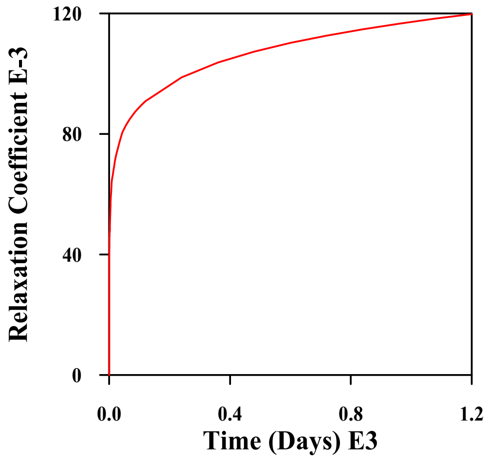


Fig. 10 Variation of time dependent material properties for prestressed steel

Variation of time dependent material properties used for concrete and prestressed steel is given in Figs. 8-10. These parameters are selected from CEB-FIP design code (CEB-FIP 1990) in SAP2000. According to the parameters given in Table 3, these graphics may be changed automatically.

6. Construction stage analysis

To assess of structural behavior of suspension bridges considering construction stages and different soil conditions, Bosporus Suspension Bridge is selected as an example. This bridge has a main span of 1560 m and two side spans of 231 m and 255 m on the European and the Asian sides respectively, without any side spans supported by cables. The bridge has flexible steel towers of 165 m high, inclined hangers and a steel box-deck. The horizontal distance between the cables is 28 m and the roadway is 21 m wide, accommodating three lanes each way. Analysis is performed

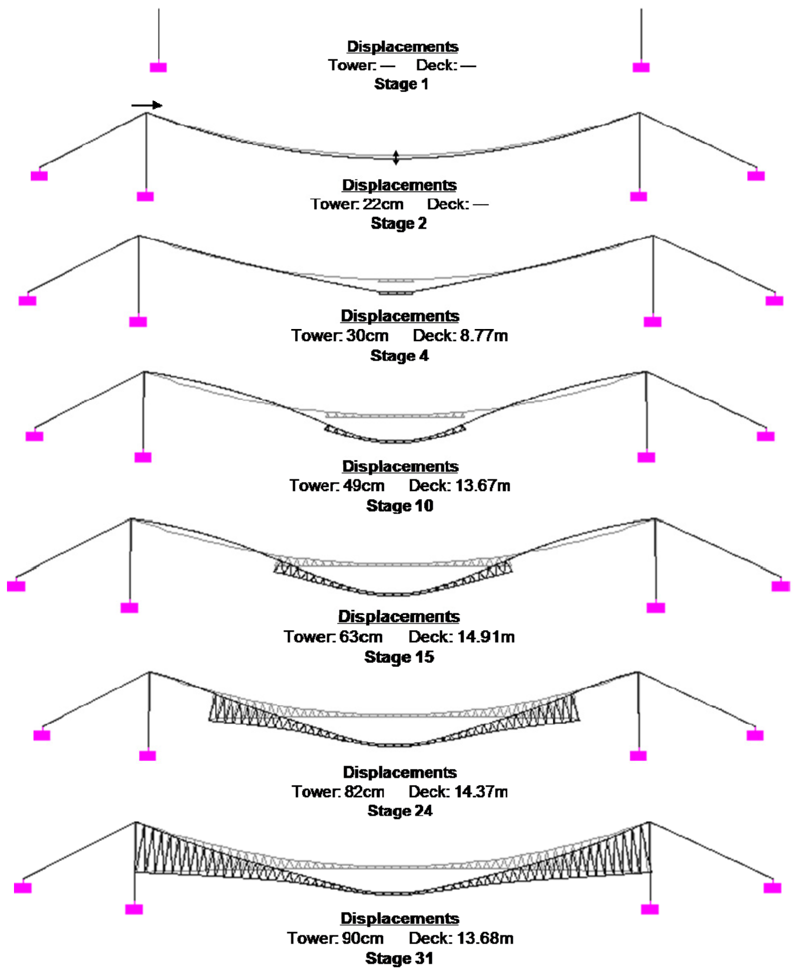


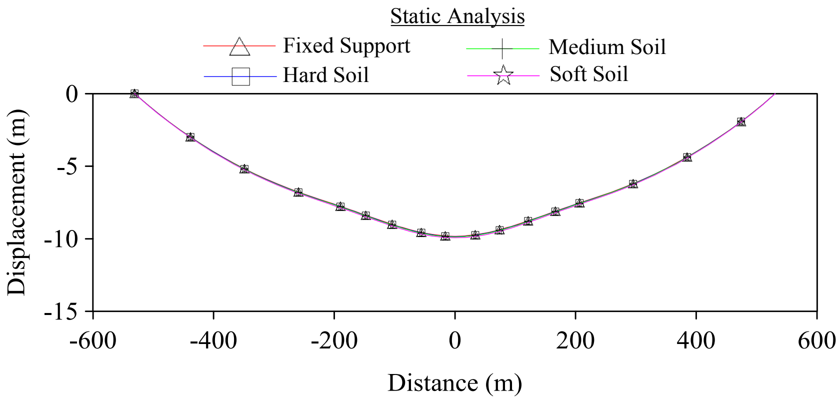
Fig. 11 Deformation of Bosporus Suspension Bridge during some construction stages

using SAP2000 program. Nonlinear staged construction and P-Delta plus large displacements options are selected as analysis type and geometric nonlinearity parameters, respectively.

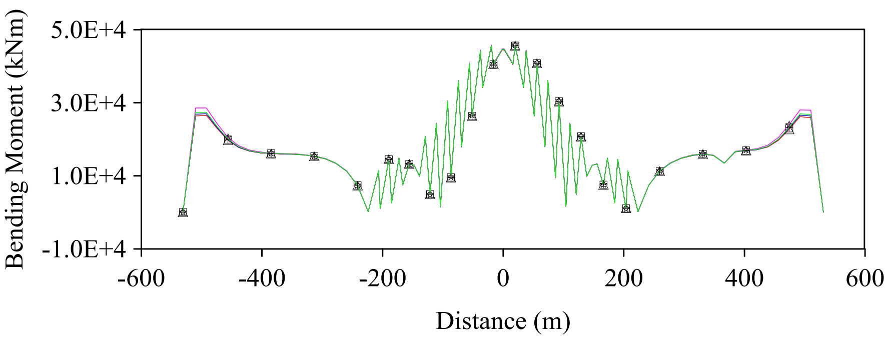
6.1 Deformation shapes

The deformations of the bridge at some construction stages considering fixed support are plotted and the maximum vertical displacements of the bridge deck and maximum horizontal displacements of the bridge tower are also given in Fig. 11. It is seen that displacements increase along the middle of the bridge deck and along the height of the bridge towers. The deformations of the bridge taken from the analyses are obtained similar to (Fig. 11) the fixed support condition when the soil-structure interaction is considered. Thus, the vertical displacements obtained in hard, medium and soft soil conditions and the horizontal displacements formed in the towers are not given as a figure.

It is seen that displacements increase along the middle of the bridge deck and reach a maximum of 15.00 m at the 18th stage for the analysis including the construction stage. When the construction of the bridge is completed at the 31st stage, maximum displacement is obtained as 13.68 m at the middle point of the bridge deck. In addition to this, variation of the displacement increases along the height of the bridge towers and reach a maximum of 90 cm at the 31st stage.



(a) Displacements



(b) Bending moments

Fig. 12 Changing of maximum (a) displacements; and (b) bending moments along the bridge deck

7. Numerical results

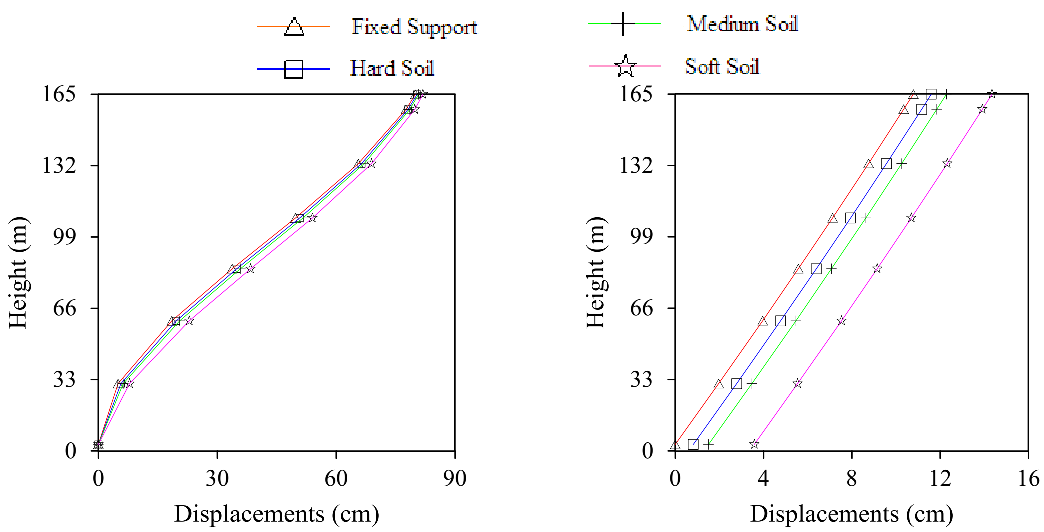
7.1 Static analysis

Distributions of vertical displacements and bending moments along the bridge deck are given in Fig. 12. It is seen that displacements have an increasing trend towards to the middle of the bridge deck and reach a maximum of 9.94 m at the middle for the static analyses. The values of bending moments are obtained symmetrically according to the middle point of the bridge deck and reach a maximum of 4.5E4kNm at the middle for the static analyses. It is seen from Fig. 12 that the values of the displacements and bending moments for all soil conditions are approximately the same.

Variation of maximum horizontal and vertical displacements along the height of the European side tower is shown in Fig. 13. It can easily be seen that the horizontal displacements increase with the height of bridge tower and reach a maximum of 82 cm at the top when the soft soil condition is considered. Also, the values of the horizontal displacement obtained at the top of the bridge tower as 80 cm and 81 cm when the soil conditions are considered as hard soil and medium soil respectively for the static analyses.

The maximum vertical displacements occur at the soft soil condition and reach a maximum of 14.3 cm at the top for the static analyses. The maximum vertical displacement occurred at the top of the bridge tower as 12.28 cm, 11.59 cm and 10.78 cm when the soil conditions are considered as medium soil and hard soil and fixed support condition respectively for the static analyses. It can be seen that both maximum horizontal and vertical displacement occurred at the top of the bridge tower when the soft soil conditions are considered.

Fig. 14 points out the internal forces such as axial and shear forces of the European side tower. The values of the axial forces are nearly equal along the height of the bridge tower for all soil conditions. Axial forces decrease from the base (-1.9E5kN) to the top of the point (-1.7E5kN)



(a) Horizantal (b) Vertical

Fig. 13 Changing of displacements along to the height of the European side tower for the static analyses. The values of the shear forces are nearly equal along the height of the bridge tower as -1830 kN, -1760 kN, -1710 kN and -1570 kN when the soil conditions are considered as fixed support, hard soil, medium soil and soft soil respectively for the static analyses. It is seen from Fig. 14 that the values of the maximum shear forces obtained for soft soil conditions.

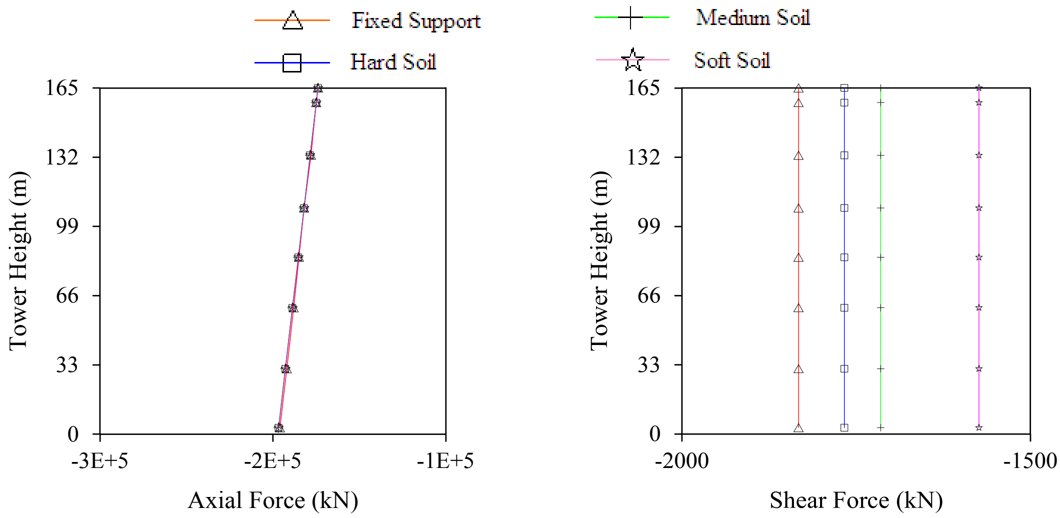
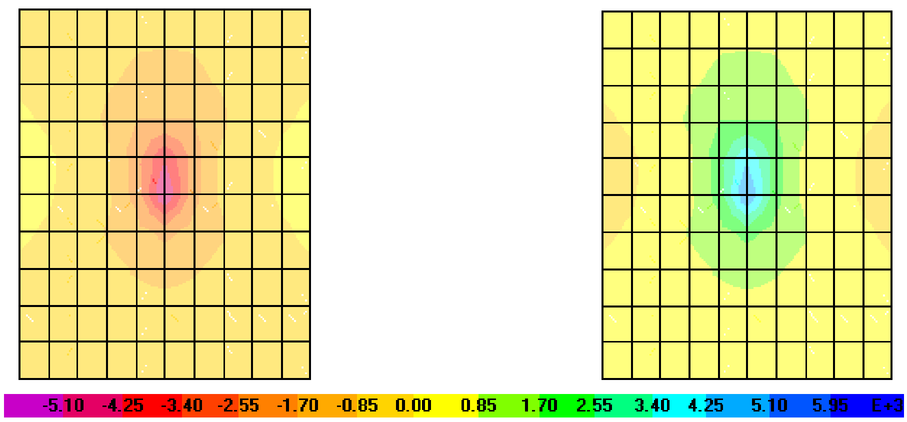


Fig. 14 Changing of internal forces along the height of the bridge tower

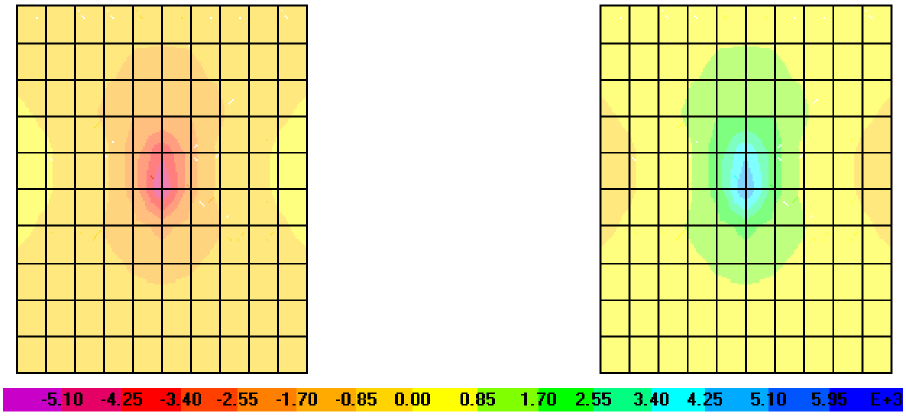
Table 4 Vertical displacements of the foundation

Soil Types	Fixed support	Hard	Medium	Soft
Displacement (mm)	0	8.2	15.10	36

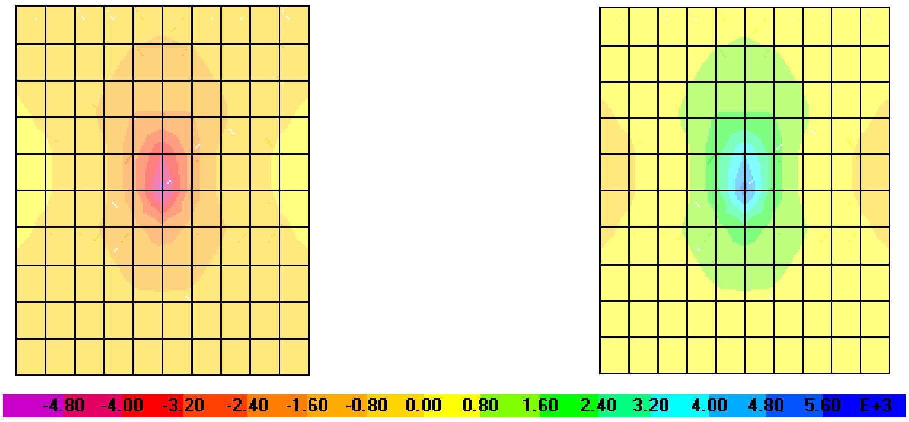


(a) Hard soil

Fig. 15 Contours graphics in the course of maximum and minimum stresses are formed which are obtained in the foundation



(b) Medium soil



(c) Soft soil

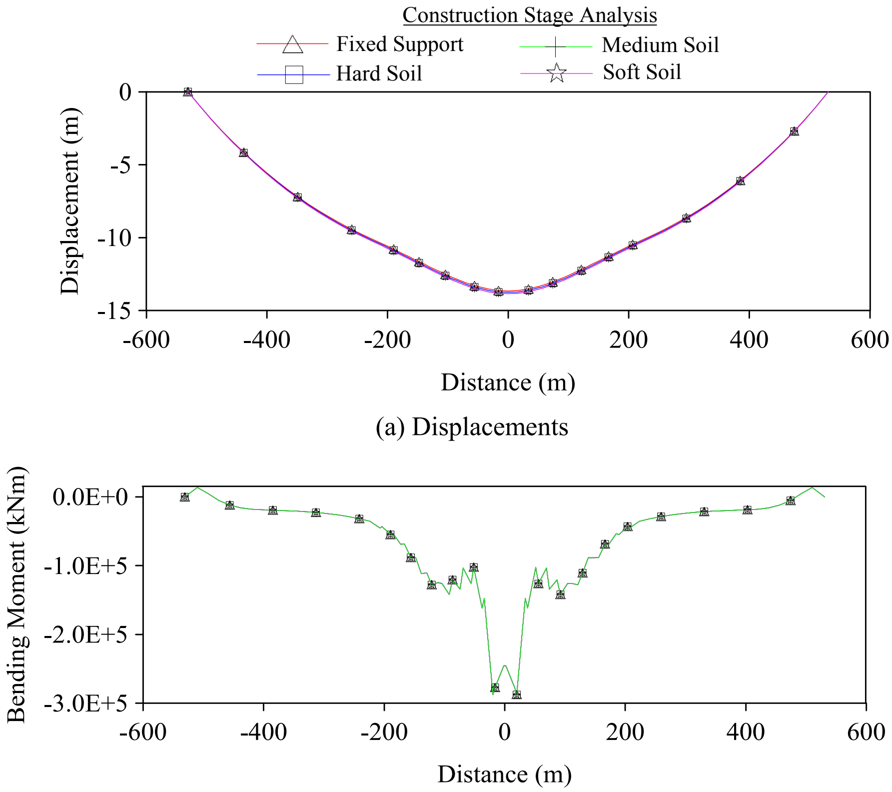
Fig. 15 Continued

Variation of maximum vertical displacements obtained at the European side foundation as a result of static analyses considering soil-structure interaction is given in Table 4. As it seen in Table 4, the vertical displacements occurred at the foundation increase from the hard soil (8.20 mm) to the soft soil (36 mm).

Contours graphics in the course of maximum and minimum stresses are formed which are obtained in the foundation are presented in Fig. 15. As it seen in Fig. 15, the maximum and minimum stresses occur as the highest for the hard soil type and the maximum and minimum stresses decrease for the medium and soft soil types. The values of the maximum and minimum stresses for all soil types were obtained at the end of the bridge tower.

7.2 Construction stage analysis

Variation of vertical displacements and bending moments along the bridge deck is shown in Fig. 16. It can easily be seen that the vertical displacements increase towards to the middle of the bridge deck and reach a maximum of 13.68 m at the middle for the analysis including the construc-



(a) Displacements

(b) Bending moments

Fig. 16 Changing of maximum (a) displacements; and (b) bending moments along the bridge deck

tion stages. The values of bending moments are obtained symmetrically according to the middle point of the bridge deck and reach a maximum of 2.8E5kNm at the middle for the analysis including the construction stages. Also, it is seen from Fig. 16 that the values of the displacements and bending moments are nearly equal when the soil-structure interaction is considered.

Variation of maximum horizontal and vertical displacements along the height of the European side tower obtained from construction stage analyses are presented in Fig. 17. It can easily be seen that the horizontal displacements increase with the height of bridge tower and reach a maximum of 90 cm at the top when the soft soil condition is considered. It can be also seen that the maximum vertical displacements come into being at the soft soil condition and reach a maximum of 16 cm at the top for the analysis including the construction stages.

Changing internal forces such as axial and shear forces of the European side tower are shown in Fig. 18. The values of the axial forces are nearly equal along the height of the bridge tower for both soil conditions and have a decreasing trend from the base to the top of the bridge tower. The values of the shear forces are changeable along the height of the bridge tower. The shear forces occur as the highest for the fixed support condition and have a decreasing trend for the other soil types. The maximum shear forces obtained as 2.9E3kN along the height of the bridge tower for the analysis including the construction stages.

Variation of maximum vertical displacements obtained at the European side foundation as a result of construction stage analyses considering soil-structure interaction is given in Table 5. As it seen in Table 5, the vertical displacements obtained at the foundation increase from the hard soil (11.30 mm) to the soft soil (40 mm).

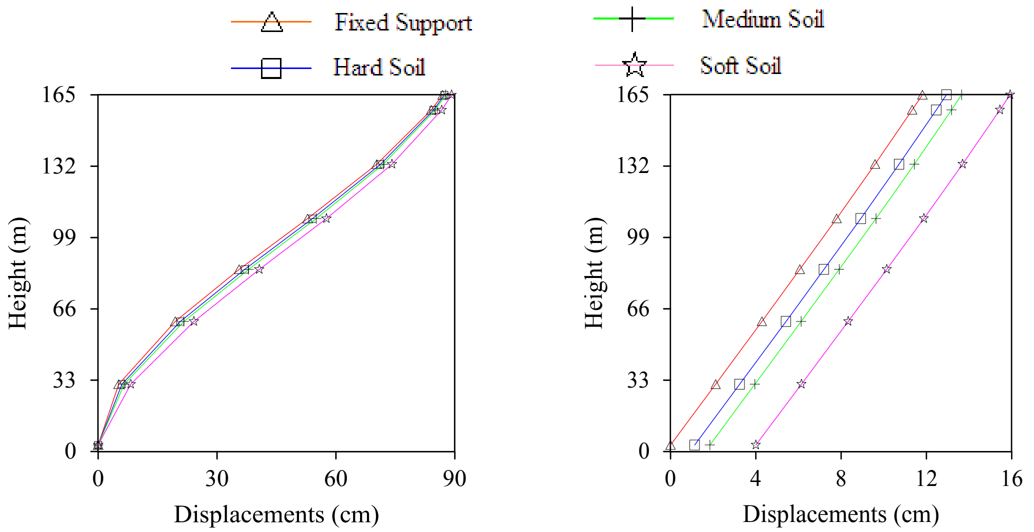


Fig. 17 Changing of displacements along to the height of the European side tower

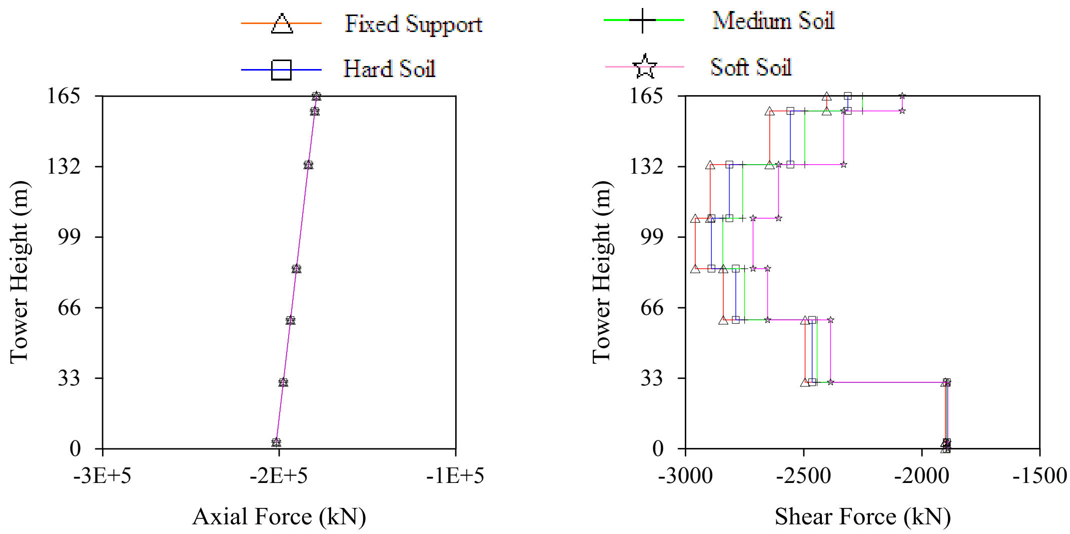
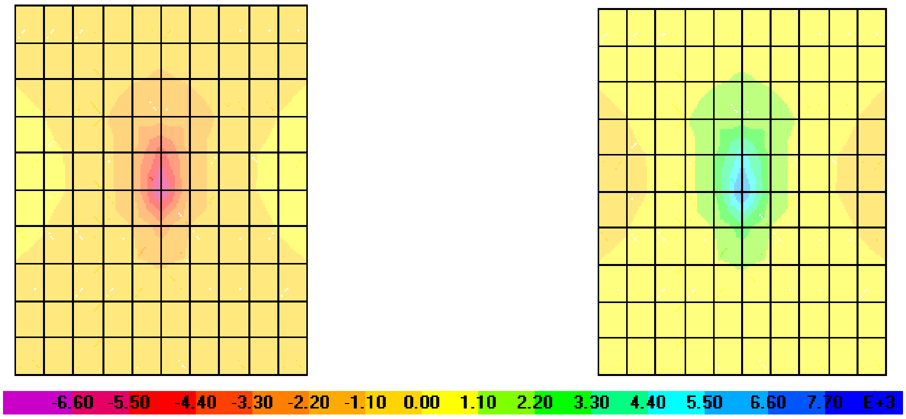


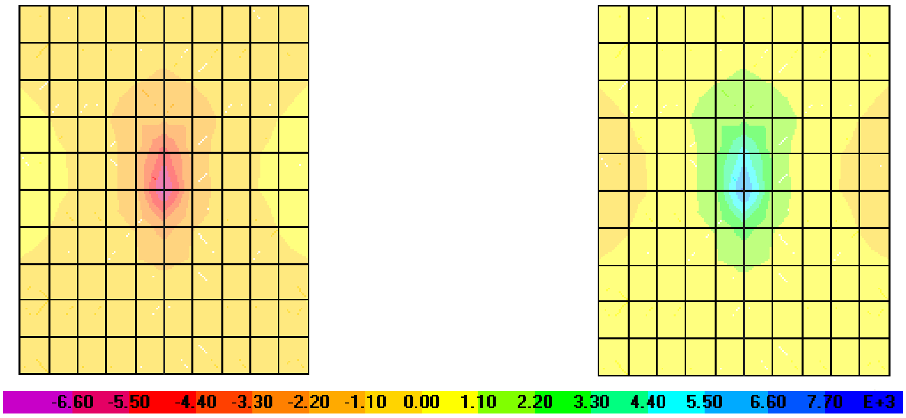
Fig. 18 Changing of axial and shear forces along the height of the bridge tower

Table 5 Vertical displacements of the foundation

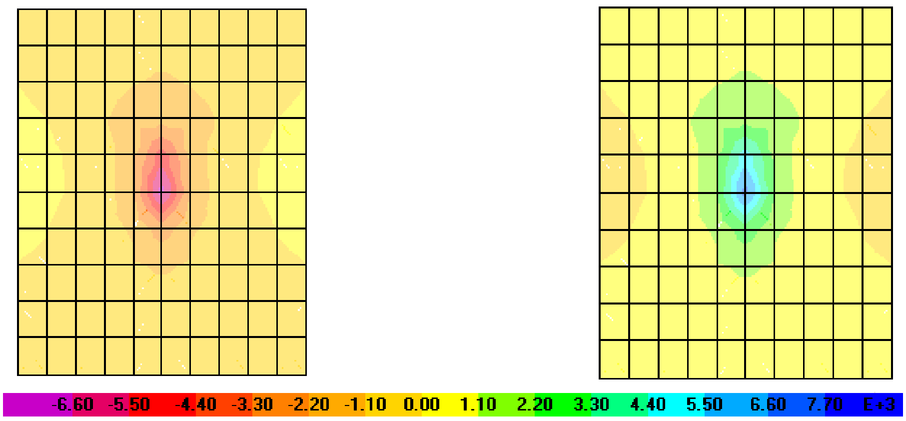
Soil types	Fixed support	Hard	Medium	Soft
Displacement (mm)	0	11.30	19.00	40



(a) Hard soil



(b) Medium soil



(c) Soft soil

Fig. 19 Contours graphics in the course of maximum and minimum stresses are formed which are obtained in the foundation

Contours graphics in the course of maximum and minimum stresses are formed which are obtained in the foundation are presented in Fig. 19. As it seen in Fig. 19, the maximum and minimum stresses occur as the highest for the hard soil type and the maximum and minimum stresses decrease for the medium and soft soil types. The values of the maximum and minimum stresses for all soil types were obtained at the end of the bridge tower.

8. Conclusions

The main objective of this study is to determine of structural behavior of suspension bridges considering construction stages and different soil conditions. The time dependent material properties of concrete and steel are also considered. Bosporus Suspension Bridge is selected as an example. The P-Delta plus large displacement is employed in the geometrical nonlinear analysis. The time dependent material strength variations and geometric variations are included in the analysis. Comparing the results of the study, the following observations can be made:

- When the displacements and bending moments obtained along the bridge deck are examined, it is seen that the values are nearly equal for static and construction stage analyses, separately. Its mean that the values of the displacements and bending moments for all soil conditions are approximately the same.
- When the axial forces obtained along the bridge tower are examined, it is seen that the values are nearly equal for static and construction stage analyses, separately. Its mean that the values of the axial forces for all soil conditions are approximately the same.
- The vertical displacements increase towards to the middle of the bridge deck and reach a maximum of 13.68 m at the middle for the analysis including the construction stages. On the other hand, maximum displacement is 9.94 m at the middle for the analysis not including construction stage. The difference is reached to 3.74 m at the middle of the bridge deck.
- The maximum horizontal and vertical displacements at the tower occur at the soft soil condition for both analyses. The horizontal and vertical displacements increase with the height of bridge tower and reach a maximum of 90 cm and 16 cm at the top for the analysis including the construction stage. Yet, the value of the horizontal and vertical displacement with the height of bridge towers is 82 cm and 14.30 cm for the analysis not including the construction stage. Also, the values of the horizontal displacement obtained at the top of the bridge tower as 80 cm and 81 cm when the soil conditions are considered as hard soil and medium soil respectively for the static analyses. The maximum vertical displacement occurred at the top of the bridge tower as 12.28 cm, 11.59 cm and 10.78 cm when the soil conditions are considered as medium soil and hard soil and fixed support condition respectively for the static analyses.
- Maximum bending moment at the deck occurred as 2.8E5kNm at the middle for the analysis including the construction stages. On the other hand, maximum bending moments occurred as of 4.5E4kNm at the middle for the analysis not including the construction stage. The values of bending moments obtained from the analyses including construction stages are significantly bigger than those of not including the construction stages.
- The values of the axial forces for both static analyses and construction stage analyses are nearly equal along the height of bridge tower. Axial forces decrease from the base (-1.9E5 kN) to the top of the point (-1.7E5 kN). The maximum shear forces at the tower occur for the fixed support conditions for both analyses. The values of the shear forces are changeable

along the height of the bridge tower for the analysis including the construction stage. Shear forces increase non-linearly from the base (-1.9E3 kN) to the middle point (-2.9E3 kN) and decrease non-linearly from the middle point (-2.9E3kN) to the top point (-2.4E3 kN) for the analysis including the construction stage, but the values of the shear forces are nearly equal along the height of the bridge tower as 1.8E3 kN for the analysis not including the construction stage.

- The vertical displacement obtained at the foundation, while the construction stage analysis is considered, increase from the hard soil (11.30 mm) to the soft soil (40 mm). But, the vertical displacement obtained at the foundation, while the construction stage analysis is not considered, increase from the hard soil (8.20 mm) to the soft soil (36 mm).
- There are some differences between the results with and without the construction stages. It can be stated that the analysis without construction stages cannot give the reliable solutions. Also, types of soil condition have effect on the results of analysis such as displacements and internal forces obtained tower, deck and base of tower.
- In this paper, both of the construction stages and time dependent material properties are considered in the finite element analysis of the bridge. The analyses can be divided into three groups as construction stages analyses, time dependent material properties and, construction stages analyses with time dependent material properties. At the end of the analyses, the differences can be obtained and which analysis has an important effect on the structural elements of suspension bridges (concrete girder, hanger, cable and tower) can be investigated.

To obtain real behaviour of engineering structures, construction stage analysis considering different soil conditions using time dependent material strength variations, geometric variations and soil-structure interaction should be done. Especially it is very important for suspension bridges, because construction period continue along time and loads may be change during this period.

References

Adanur, S. and Günaydın, M. (2010), "Construction stage analysis of bosporus suspension bridge", *Proceeding of 9th International Congress on Advances in Civil Engineering*, Trabzon, Turkey, September.

Adanur, S., Gunaydin, M., Altunisik, A.C. and Sevim, B. (2012), "Construction stage analysis of Humber Suspension Bridge", *Appl. Math. Model.*, **36**(11), 5492-5505.

Altunışık, A.C. (2010), "Determination of structural behaviour highway bridges using analytical and experimental methods", Ph.D. Thesis, Karadeniz Technical University, Trabzon, Turkey. [In Turkish]

Altunışık, A.C., Bayraktar, A., Sevim, B., Adanur, S. and Domaniç, A. (2010), "Construction stage analysis of kömürhan highway bridge using time dependent material properties", *Struct. Eng. Mech.. Int. J.*, **36**(2), 207-244.

Ateş, Ş. (2010), "Numerical modelling of continuous concrete box girder bridges considering construction stages", *Appl. Math. Model.*, **35**(8), 3809-3820.

Ateş, Ş., Atmaca, B., Yıldırım, E. and Demiröz, N.A. (2013), "Effects of soil-structure interaction on construction stage analysis of highway bridges", *Comput. Concrete*, **12**(2), 169-186.

Brownjohn, J.M.W., Magalhaes, F., Caetano, E. and Cunha, A. (2010), "Ambient vibration re-testing and operational modal analysis of the Humber Bridge", *Eng. Struct.*, **32**(8), 2003-2018.

CEB-FIP Model Code (1990), *Thomas Telford*, ISBN: 0727716964.

Cheng, J., Jiang, J.J., Xiao, R.C. and Xia, M. (2003), "Wind-induced load capacity analysis and parametric study of a long-span steel arch bridge under construction", *Comput. Struct.*, **81**(26-27), 2513-2524.

Cho, T. and Kim, T.S. (2008), "Probabilistic risk assessment for the construction phases of a bridge

construction based on finite element analysis", *Finite Elem*. *Anal*. *Des*., **44**(6-7), 383-400.
Gunaydin, M., Adanur, S., Altunısık, A.C. and Barıs, S. (2012), "Construction stage analysis of Fatih Sultan Mehmet Suspension Bridge'' *Struct*. *Eng*. *Mech*., *Int*. *J*., **42**(4), 489-505.
Karakaplan, A., Caner, A., Kurç, Ö,. Domaniç, A. and Lüleç, A. (2007), "New strategy in the structural analysis: construction stage", *Proceeding of 1st Symposium of Bridges and Viaducts*, Antalya, Turkey, November.
Ko, J.M., Xue, S.D. and Xu, Y.L. (1998), "Modal analysis of suspension bridge deck units in erection stage", *Eng*. *Struct*., **20**(12), 1102-1112.
Kwak, H.G. and Seo, Y.J. (2002), "Numerical analysis of time-dependent behaviour of pre- cast pre-stressed concrete girder bridges", *Construct*. *Build*. *Mater*., **16**(1), 49-63.
Pindado, S., Meseguer, J. and Franchini, S. (2005), "The influence of the section shape of box-girder decks on the steady aerodynamic yawing moment of double cantilever bridges under construction", *J. Wind Eng*. *Ind*. *Aerod*., **93**(7), 547-555.
SAP2000 (2008), *Integrated Finite Element Analysis and Design of Structures*, Computers and Structures Inc., Berkeley, CA, USA.
Somja, H. and Goyet, V.V. (2008), "A new strategy for analysis of erection stages including an efficient method for creep analysis", *Eng*. *Struct*., **30**(10), 2871-2883.
Soyluk, K., Diri, T.G. and Sıcacık, E.A. (2010), "Time dependent nonlinear analysis of segmentally erected cable-stayed bridges", *Proceeding of 9th International Congress on Advances in Civil Engineering*, Trabzon, Turkey, September.
Wang, P.H., Tang, T.Y. and Zheng, H.N. (2004), "Analysis of cable-stayed bridges during construction by cantilever methods", *Comput*. *Struct*., **82**(4-5), 329-346.

CC

Nomenclature

A_c	cross-section
E	modulus of elasticity
E_{ci}	modulus of elasticity at age of 28 days
F	force vector
f_{cm}	concrete compressive strength at age of 28 days
H	notional size of member (mm)
K	stiffness matrix
RH	relative humidity of the ambient atmosphere (%)
t	time
U	displacement vector
β_{cc}	coefficient with depends on the age of concrete
ε_{esp}	notional shrinkage coefficient
β_s	coefficient to describe the development of shrinkage with time
β_{sc}	coefficient ranging from 4 to 8 which depends on the type of cement
σ_c	stress
Φ	creep coefficient
β_c	coefficient to describe the development of creep with time after loading
ρ	relaxation