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Effects of soil-structure interaction on construction stage analysis of highway bridges

Sevket Ates[1a], Barbaros Atmaca[*1], Erdal Yildirim[1b] and Nurcan Asci Demiroz[2c]

[1]*Department of Civil Engineering, Karadeniz Technical University, 61080 Trabzon, Turkey*
[2]*Department of Civil Engineering, Avrasya University, 61250 Yomra, Trabzon, Turkey*

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Abstract. The aim of this paper is to determine the effect of soil-structure interaction and time dependent material properties on behavior of concrete box-girder highway bridges. Two different finite element analyses, one stage and construction stage, have been carried out on Komurhan Bridge between Elazığ and Malatya province of Turkey, over Fırat River. The one stage analysis assume that structure was built in a second and material properties of structure not change under different loads and site conditions during time. However, construction stage analysis considers that construction time and time dependent material properties. The main and side spans of bridge are 135 m and 76 m, respectively. The bridge had been constructed in 3 years between 1983 and 1986 by balanced cantilever construction method. The parameters of soil-structure interaction (SSI), time dependent material properties and construction method are taken into consideration in the construction stage analysis while SSI is single parameter taking into consideration in the one stage analysis. The 3D finite element model of bridge is created the commercial program of SAP2000. Time dependent material properties are elasticity modulus, creep and shrinkage for concrete and relaxation for steel. Soft, medium, and firm soils are selected for evaluating SSI in both analyses. The results of two different finite element analyses are compared with each other. It is seen that both construction stage and SSI have a remarkable effect on the structural behavior of the bridge.

Keywords: construction stage analysis; soil-structure interaction; time dependent material properties; balanced cantilever method; finite element analysis; Komurhan Bridge

1. Introduction

Bridges are indispensable components of transportation network and their construction cost is very high from other components. Damaging of bridges cause disconnection of roads also loss of life and property for these reasons, understanding of real structural behavior of bridges is becoming vital for engineers. There are several bridge types and construction methods of them. One of the most using bridge type is box-girder concrete. In this type of bridge cantilever construction method is preferred. Cantilever method is especially recommended where scaffolding

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[*] Corresponding author, Ph.D Student, E-mail: atmaca@ktu.edu.tr
[a] Associate Professor
[b] Civil Engineer, MSc
[c] Assistant Professor

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is difficult or impossible to construct over deep valleys, wide rivers or in case of expensive foundation conditions for scaffolds. There are two basic alternatives in the cantilever method. One is single cantilever method and the other is the double cantilever method. In the former method, the side span girders of the bridge are constructed on temporary piers and afterwards the stiffening girder in main span is constructed by one-sided free cantilevering until the span center or the anchor pier on the far end is reached. In the latter, the bridge girder is constructed from both side of the tower towards the anchor piers and the main span center by double-sided free cantilevering. The double cantilever method is also named as the balanced cantilever method.

The most preferred method of determine the static and dynamic behavior of structure is finite element analysis. Normally, in this analysis structures are analyzed by assuming that engineering structures are instantly built in a time. In addition, properties of structural materials using on structure are thought not chancing with time and site conditions. This type of analysis may be give unreliable results. Especially constructions of large engineering structures keeps going years and during the construction changing of material properties are inevitable. However, in the construction stage analysis time dependent material properties and construction stages taken into account. Because the material properties of concrete and steel change under different load patterns and weather conditions during time. The analysis of large engineering structure according to the construction process like in the site will provide more realistic results to obtain. In recent years, many interesting research topics have arisen such as analysis that taken in to account segmentally construction stages. Several studies have dealt with the analysis of segmentally constructed bridges, as long as a few studies have been struggled the analysis of the deflection and internal moment redistribution in bridges (Ketchum 1986, Bishara and Papakonstantinou 1990, Chiu *et al.* 1996). Structural design methods may neglect the SSI effects. Neglecting SSI is reasonable for light structures in relatively stiff soil such as low rise buildings and simple rigid retaining walls. The effect of SSI becomes prominent for heavy structures resting on relatively soft soils for example nuclear power plants, high-rise buildings and elevated-highways on soft soil (Wolf 1985). Abbas and Scordelis (1993) achieved nonlinear geometric, material and time dependent analysis of segmentally erected three-dimensional cable stayed bridges. Cruz *et al.* (1998) presented a general step by step model for the nonlinear and time dependent analysis of reinforced, prestressed concrete, and composite steel-concrete planar frame structures. Daloglu and Vallabhan (2000) were used non-dimensional parameters for the analysis of a slab on a layered soil medium, and developed a method to evaluate an equivalent modulus of subgrade reaction to be used in the Winkler model. Kwak and Son (2002, 2004) studied on span ratios in bridges constructed using a balanced cantilever method and reported that moment variation due to the change in structural system during construction requires a rigorous time dependent analysis that considers the construction stages. Wang *et al.* (2004) carried out the analysis of cable stayed bridges at different stages during construction by the cantilever method. Pindado *et al.* (2005) investigated the influence of the section shape of box girder decks on the moments during construction stages experimentally. Somja and Goyet (2008) came up with an efficient numerical procedure for materially and geometrically nonlinear finite element analysis of segmentally erected structures including time dependent effects due to load history, creep, shrinkage and aging of concrete. In that study, it was observed that time affects have a strong influence, especially, on concrete type structures. Therefore, it was emphasized that these effects must be taken into account in the design process. Bayraktar *et al.* (2009) and Altunisik *et al.* (2010) studied the construction stage analysis of highway bridges constructed with balanced cantilever method using time dependent material properties and obtained that construction stage analysis has remarkable effect on the structural behavior of the bridge. Ates (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 behavior of the bridge at different construction stages has been examined. As analyses result, variation of internal forces such as bending moment, shear forces and axial forces, and displacements for bridge deck and pier are given with detail. Atmaca and Ates (2012) studied about analytical modelling of cable-stayed bridge considering construction stages. The structural behavior of the bridge under construction stage and without construction stage analysis compared with each other. Adanur *et al*. (2012) and Gunaydin *et al*. (2012) studied about analytical modelling of suspension bridge considering construction stages. Likatanyu *et al*. (2012) studied on alternative way to derive the exact element stiffness matrix for a beam on Winkler foundation and the fixed-end force vector due to a linearly distributed load.

As seen in literature, there are several researches about the construction stage analysis of structures and soil-structure interaction but there is no sufficient research considering both construction stage analysis and soil-structure interaction. So in this paper box-girder concrete Komurhan Bridge constructed with balanced cantilever method is selected as an application to obtain the effect of construction stage and different types of soil on structural behavior of the bridge. Construction stage analysis of three dimensional model of the bridge is performed with using time dependent material properties and SSI effect.

2. Formulation

In order to determine the effect of material properties for structural behavior of Komurhan Bridge, relaxation of steel material, creep, shrinkage and aging of concrete are taken into account.

2.1 Time dependent properties for concrete

2.1.1 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-FIB 1990)

$$f_{cm}(t) = \beta_{cc}(t)\, f_{cm} \tag{1}$$

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

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

$f_{cm}(t)$ 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. The mean concrete compressive strength is given in Fig. 1.

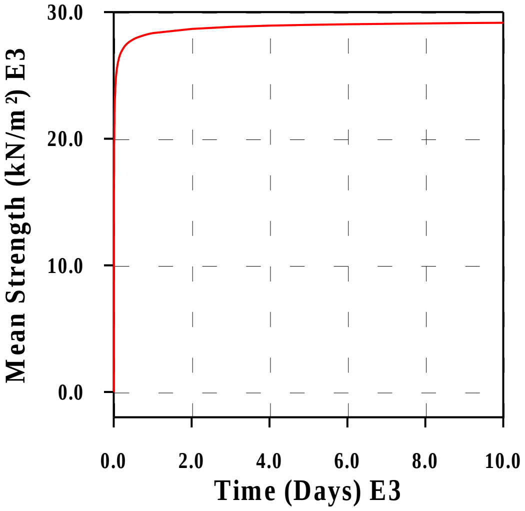


Fig. 1 Variation of the mean concrete compressive strength with days

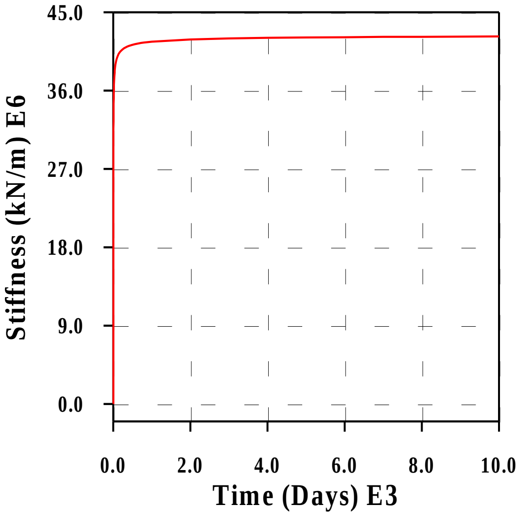


Fig. 2 Aging of concrete in days

2.1.2 Aging of concrete

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

$$E_{ci}(t) = E_{ci}\sqrt{\beta_{cc}(t)} \tag{3}$$

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. For the bridge, the aging of concrete is plotted in Fig. 2

2.1.3 Shrinkage of concrete

The CEB-FIP Model Code (1990) gives the following equation of total shrinkage strain of concrete

$$\varepsilon_{cs}(t, t_s) = \varepsilon_{cso}\beta_s(t - t_s) \tag{4}$$

where ε_{cso} is notional shrinkage coefficient; β_s 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

$$\varepsilon_{cso} = \varepsilon_s(f_{cm})\beta_{RH} \tag{5a}$$

$$\varepsilon_s(f_{cm}) = \left[160 + 10\beta_{sc}(9 - \frac{f_{cm}}{f_{cmo}})\right] \tag{5b}$$

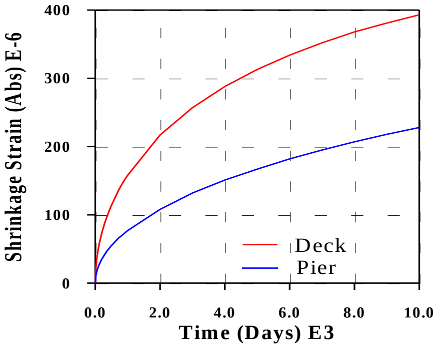


Fig. 3 Time dependent shrinkage strain of concrete

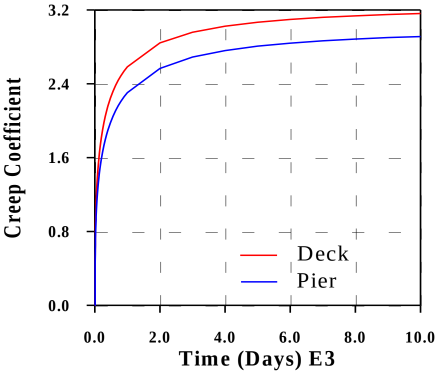


Fig. 4 Time dependent creep coefficient

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.

$$\begin{aligned} \beta_{RH} &= -1.55\beta_{sRH} \qquad 40\% \leq RH < 99\% \\ \beta_{RH} &= 0.25 \qquad\qquad RH \geq 99\% \end{aligned} \tag{6}$$

where

$$\beta_{sRH} = 1 - \left(\frac{RH}{RH_o} \right)^3 \tag{7}$$

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

$$\beta_s(t - t_s) = \sqrt{\frac{(t - t_s)/t_1}{350(h/h_o) + (t - t_s)/t_1}} \tag{8}$$

where h is the notional size of member (mm) and is calculated by h=2A_o/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. For the deck and the piers of the example bridge, the shrinkage strain of concrete depending on relative humidity, notional size and shrinkage coefficient is depicted in Fig. 3.

2.1.4 Creep

The effect is calculated using creep model. For a constant stress applied at time t_o, this leads to

$$\varepsilon_{cc}(t,t_o)=\frac{\sigma_c(t_o)}{E_{ci}}\phi(t,t_o) \qquad (9)$$

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

$$\phi(t,t_o)=\beta_c(t-t_o)\phi_o \qquad (10)$$

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

$$\phi_o=\phi_{RH}\beta(f_{cm})\beta(t_o) \qquad (11a)$$

$$\phi_{RH}=1+\frac{1-\left(\dfrac{RH}{RH_o}\right)}{0.46\left(\dfrac{h}{h_o}\right)^{1/3}} \qquad (11b)$$

$$\beta(f_{RH})=\frac{5.3}{\sqrt{\dfrac{f_{cm}}{f_{cmo}}}} \qquad (11c)$$

$$\beta(t_o)=\frac{1}{0.1+\left(\dfrac{t_o}{t_1}\right)^{0.2}} \qquad (11d)$$

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

$$\beta_c(t-t_o)=\left[\frac{(t-t_o)/t_1}{\beta_H+(t-t_o)/t_1}\right] \qquad (12a)$$

$$\beta_H=150\left\{1+\left(1.2\frac{RH}{RH_o}\right)^{18}\right\}\frac{h}{h_o}+250\leq 1500 \qquad (12b)$$

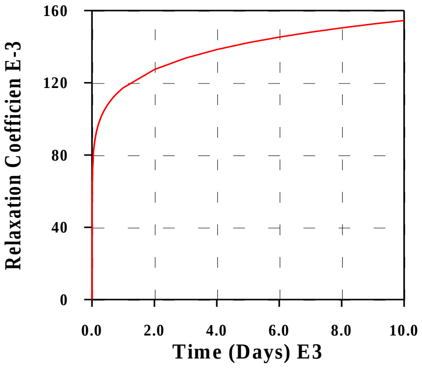


Fig. 5 Time dependent relaxation coefficient of prestressing steel

where $t_1 = 1$ day; $RH_o = 100$ and $h_o = 100$ mm. In the analysis, the creep coefficient of concrete is given in Fig. 4 for the deck and the piers having different notional size

2.1.5 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 class 2; 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. The relaxation coefficient of pre-stressing steel is given in Fig. 5.

3. Description of the bridge

Komurhan Bridge is a reinforced concrete box girder bridge located on the 51st km of Elazığ-Malatya highway. Construction of the bridge started in 1983 and completed in 1986. The bridge deck consists of 135 m main span and 76 m two side spans. The total bridge length is 287 m and width of bridge deck is 11.50 m. The structural system of Komurhan Highway Bridge (Fig. 6) consists of deck, piers, side support and expansion joint. Plan and elevation of Komurhan Bridge is given in Fig. 7.

The deck of the bridge, constructed with balanced cantilever and prestress box beam method, consists of 56 segments. All of the segments are nearly 5 m length. The height of the box girder is 9.35 m on the main piers, but it decreases parabolically to 3.5 m at the side supports and 3.0 m at the expansion joint (Fig. 8).

Fig. 6 A view of Komurhan Bridge

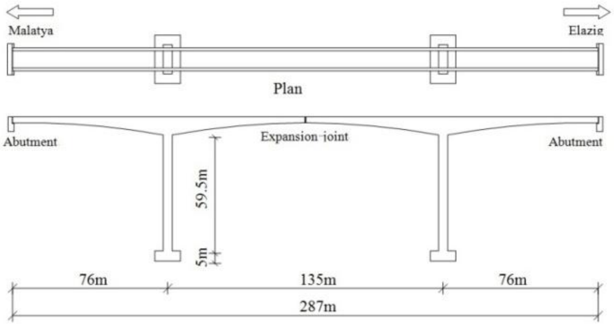


Fig. 7 Plan and elevation of the bridge

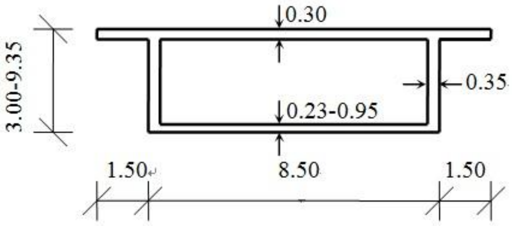


Fig. 8 The box girder deck of the bridge (Units are in meter)

There are two main piers and height of these is 59.50 m. They consist of variable sections having three cells (Fig. 9). The width of the section decreases linearly from 14.40 m at the foundation to 8.50 m at the top of the pier (Fig. 10). To combine deck cantilevers, an expansion joint is built in the main span of bridge. It consists of two IPB 600 steel beams. In this way, the edge of the cantilever at the main span is free and expansion with heat is allowed.

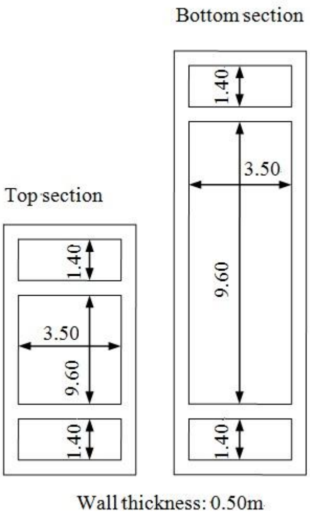


Fig. 9 Cross section of the piers (Units are in meter)

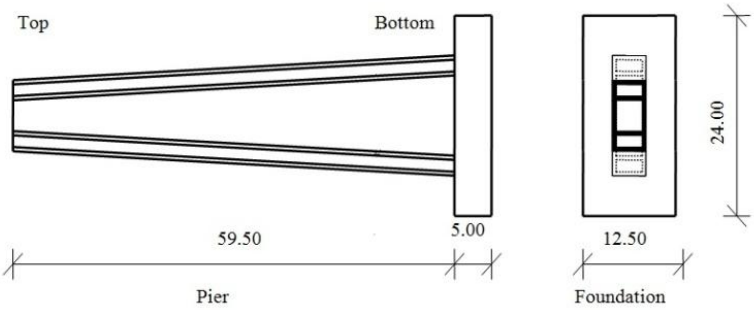


Fig. 10 Transverse section of the piers (Units are in meter)

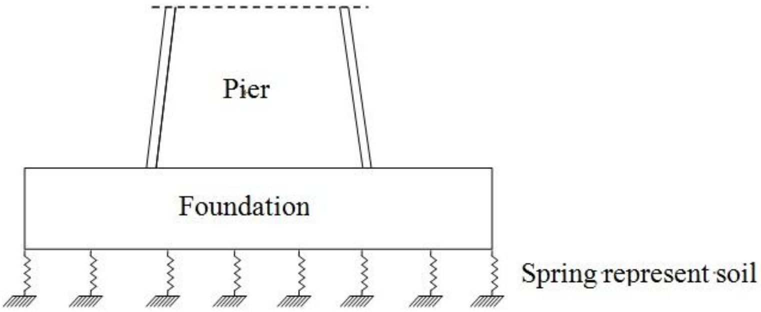
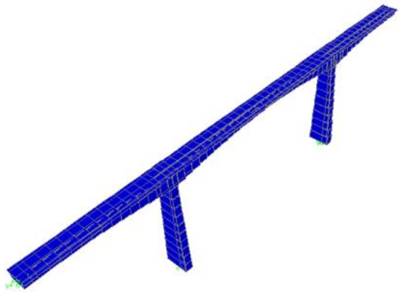
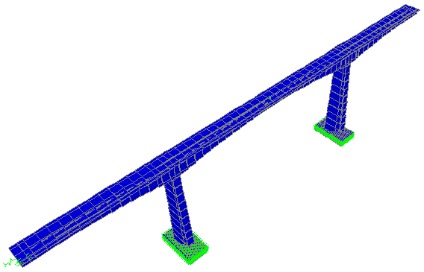


Fig. 11 Finite element foundation with equivalent soil springs



(a) Fixed base model



(b) Foundation-soil spring model

Fig. 12 Three-dimensional finite element models of Komurhan Bridge

Table 1 Different soil types and their modulus of subgrade

Soil type	Modulus of elasticity (*kN*/*m*^{2})	Modulus of subgrade (*kN*/*m*^{3})
Soft	686,000	10,290
Medium	3,308,000	49,620
Firm	5,850,000	87,750

3.1 Winkler method

The Winkler method known as equivalent soil springs method, currently this method appears to be the most widely used in a design of loaded foundation mats. The method was first introduced by Winkler (1867) to analyze the response of beams on an elastic subgrade by characterizing the soil as a series of independent linearly-elastic soil springs. With use of this method, the foundation of bridge divided finite elements and the foundation soil represented as a series of springs and these springs are nodded corners of finite elements of foundation. The schematic form of foundation of Komurhan Bridge is shown in Fig. 11 and soil properties are given Table 1.

4. Finite element analysis

The finite element model of Komurhan Bridge is modelled in the SAP2000 software and given in Fig. 12. Construction stages and time dependent material properties such as elasticity modulus, creep and shrinkage for concrete and relaxation for the pre-stressed steel are taken into account in the analysis.

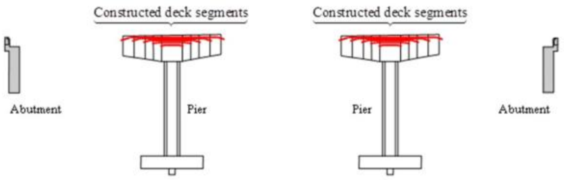


Fig. 13 The schematic view of balanced cantilever construction method

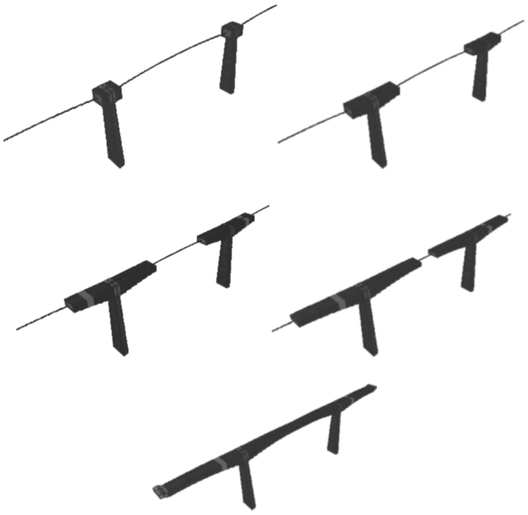


Fig. 14 Some construction stages of Komurhan Highway Bridge

Table 2 The typical operation sequence of deck segments balanced cantilever construction

Time	Working plan
1st Day	Setting up and adjusting carrier
2nd Day	Setting up and aligning forms
3rd Day	Placing reinforcement and tendon ducts
4th Day	Concreting
5th Day	Inserting prestress tendons in the segment and stressing
6th Day	Removing the form work
7th Day	Moving the form carrier to the next position and starting a new cycle

Komurhan Highway Bridge constructed with cast-in-place construction technique. Firstly, piers and abutment of bridge are constructed over substructure using suitable formwork. Then, segments (3-5 m length) are erected on opposite sides of each pier to balance the loads by using a movable form carrier. After the concreting, prestress tendons are inserted in the segments and stressed with post-tension. Finally, form carrier is moved to the next position and a new cycle starts. This sequence is completed at one week on
average and is going on until bridge decks meet at mid span. At the mid span, closure segment is established to complete one span. Because of the fact that maximum displacements are occurred at this point after finite element analysis, construction of this segment is very important. The typical

operation sequence is summarized in Table 2. The schematic view of balanced cantilever construction of prestressed concrete highway bridges is given in Fig. 13.

In the construction stage analysis, added and removed loads for each construction stages should be determined. In order to obtain the reliable solution, each stage results should be added to end of the each stage and next stage analysis is done. Additionally, nonlinear solution parameters should be selected depending on the literature.

In the finite element analysis of Komurhan Bridge, a total of 51 construction stages are considered. Total duration of all stages is calculated as 10000 days. Maximum total step and maximum iteration for each step are selected as 200 and 50, respectively. Some construction stages using SAP2000 finite element analysis program is shown in Fig. 14.

Nonlinear staged construction and P-Delta plus large displacements options are selected as analysis type and geometric nonlinearity parameters, respectively. 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. 41.15 kN/m distributed load is added to each segment considering 10 cm asphalt.

Gantry

Load of the form carrier. This load is implemented to previous one before the construction one segment and slide next one after construction of one segment. According to the final project control report, this load is calculated as 600 kN. After the construction of the bridge, this load is removed wholly.

Diaphragm

Weight of the reinforced concrete walls at the abutments and both sides of expansion joint are calculated as 1117 kN and 261 kN, respectively and added to the relevant points.

Prestress

Post-tension cables are modelled using frame elements with constrained rotations and fixed to the end of each segment. Post-tension loads are considered as strain.

4.1 Deck response

Distribution of vertical displacements values along the bridge deck with one stage and construction stage analyses are given in Figs. 15 and 16. It is seen that, vertical displacements have increasing trend towards middle of the bridge deck. In both analyses the maximum and minimum displacements occur on soft soil and without SSI situation, respectively. Types of soil have effect on deck displacement. The difference of vertical displacement between two analyses is clearly seen on Figs. 15 and 16. This difference is result of time dependent material properties effect.

Bending moments have a decreasing trend towards the middle of the bridge deck and increasing trend towards the connection point of pier and bridge deck. As shown in Fig. 17 the effect of soil types on bending moment of deck is too small on one stage analysis. But when the time dependent material properties is taken into account on construction stage analysis the effect of soil types on bending moment of deck seen clearly on Fig. 18. Max. bending moment occurs on soft soil nevertheless min moment occur on without SSI situation.

The values of shear force of the bridge deck obtaining from one stage and construction stage analysis are given in Figs. 19 and 20. As seen in these figures there is not any significant effect of

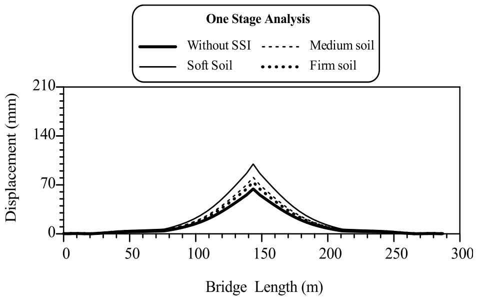


Fig. 15 Vertical displacements of the bridge deck

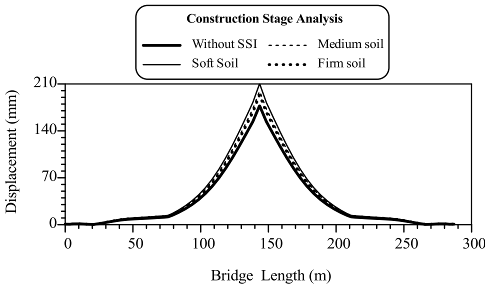


Fig. 16 Vertical displacements of the bridge deck

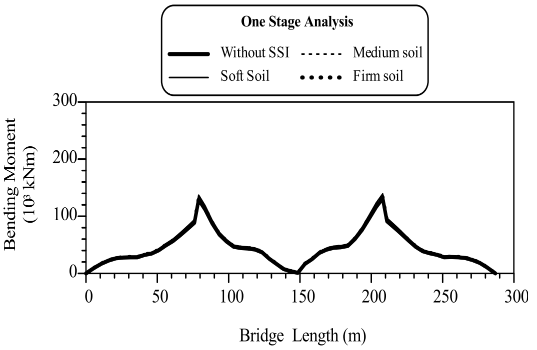


Fig. 17 Bending moment of the bridge deck

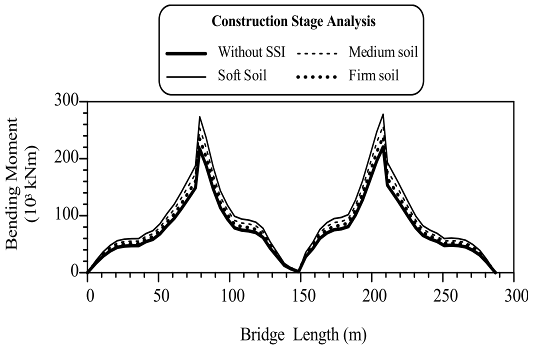


Fig. 18 Bending moment of the bridge deck

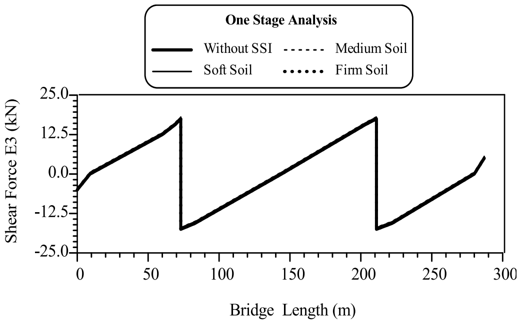


Fig. 19 Shear force of the bridge deck

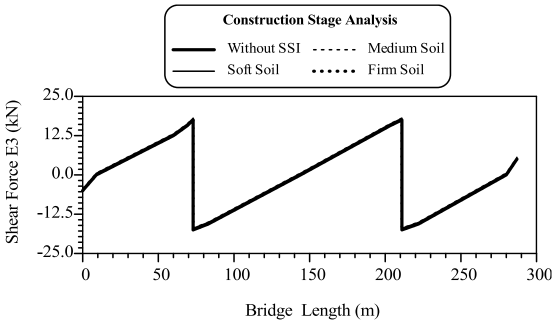


Fig. 20 Shear force of the bridge deck

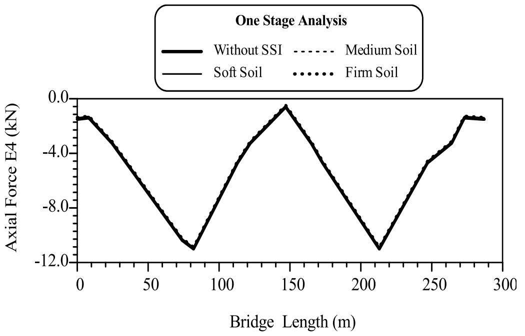


Fig. 21 Axial force of the bridge deck

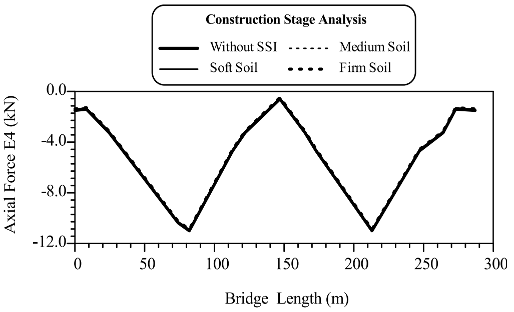


Fig. 22 Axial force of the bridge deck

soil types. Similarly there are not visible differences on distribution of shear force of the bridge deck according to types of analysis.

The values of axial force of the bridge deck obtaining from one stage and construction stage analysis are given in Figs. 21 and 22. As seen in these figures there is not any significant effect of soil types. Similarly there are not visible differences on distribution of axial force of the bridge deck according to types of analysis.

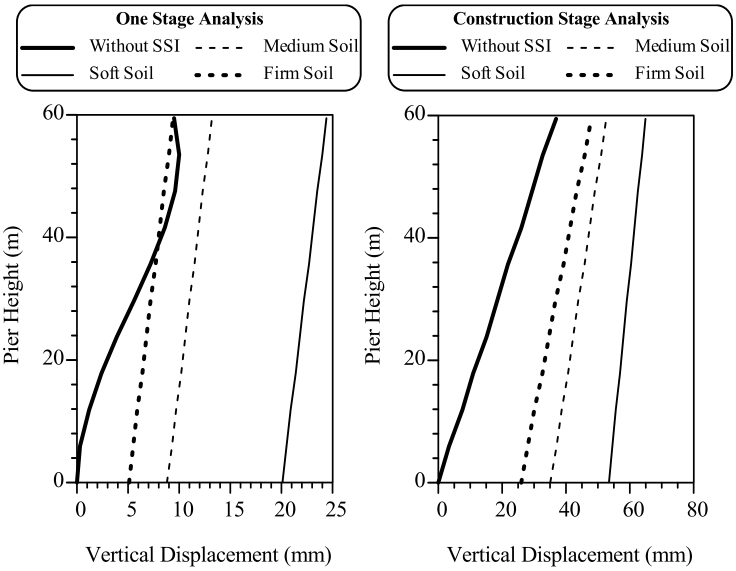


Fig. 23 Vertical displacements along the height of the bridge pier

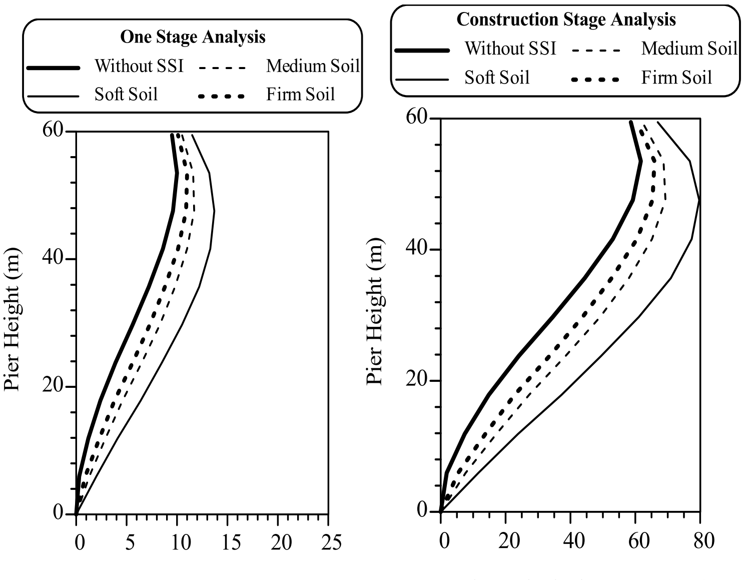


Fig. 24 Changing of displacements along the height of the bridge pier

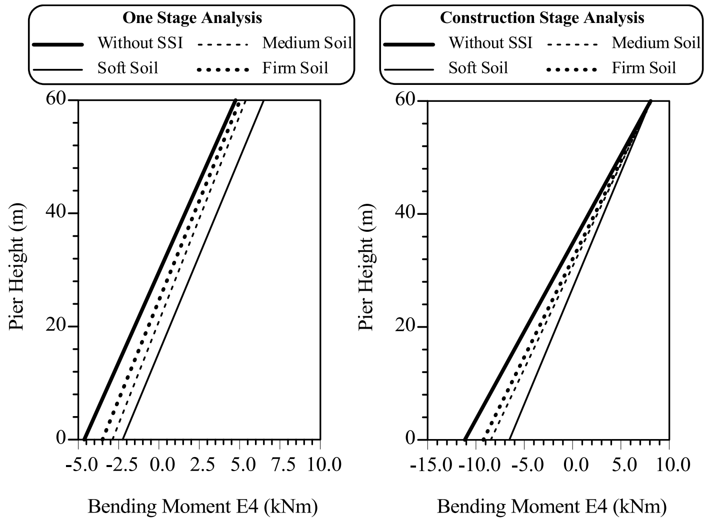


Fig. 25 Changing of bending moment along the height of the bridge pier

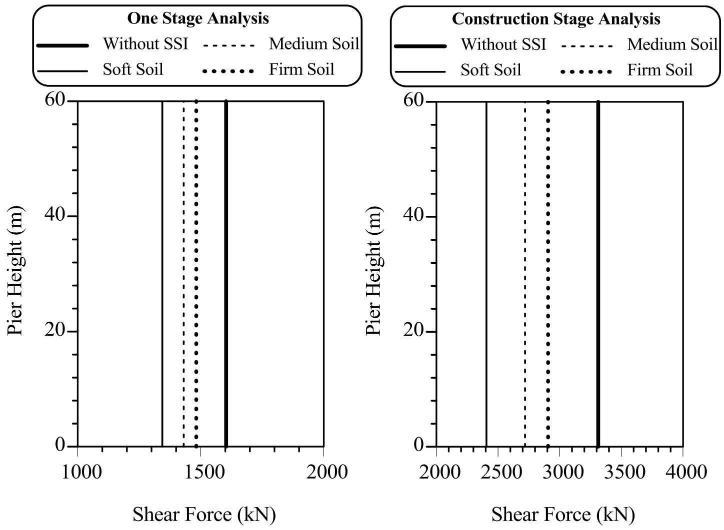


Fig. 26 Changing of shear force along the height of the bridge pier

4.2 Pier response

The vertical and horizontal displacement values of Komurhan Highway Bridge obtaining from both analyses given in Figs. 23 and 24. The effect of soil types on pier displacement also shown in Figs. 23 and 24. In both analyses maximum displacement occurs on soft soil and minimum displacement occurs on without SSI situation. The maximum vertical displacement is obtained 24.4 mm from one stage analysis 58.8 mm is obtained from construction stage analysis. The maximum horizontal displacement is obtained 13.7 mm from one stage analysis, 79.7 mm is obtained from construction stage analysis. In both analyses, obtained vertical displacement increasing along the pier height but horizontal displacements are not.

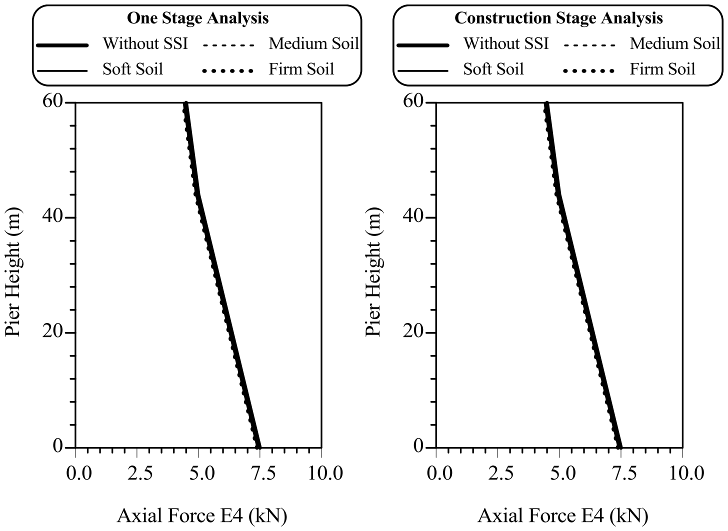


Fig. 27 Changing of axial force along the height of the bridge pier

The bending moment values of bridge pier obtaining from both analyses given in Fig. 25. As shown in Fig. 25 maximum value of bending moment of bridge pier obtained from construction stage analysis. In both analyses sign of bending moment changed in the middle of pier. Obtained values of bending moment on bottom and top of pier are different from each other according to soil types from one stage analysis. However, in construction stage analysis values of bending moment of pier on top are same. In one stage analysis the maximum absolute value of bending moment obtained from soft soil situation but in construction stage analysis obtained from without SSI situation.

The shear force values of the bridge pier obtaining from both analyses given in Fig. 26. In both analyses value of shear force approximately not change from bottom to top of pier. Obtained values of shear force on bottom and top of pier are different from each other according to soil types in both analyses. The maximum value of shear force is obtained on without SSI situation and decrease when the soil types are softened.

The values of axial force of the bridge pier from one stage and construction stage analysis are given in Fig. 27. It is seen that there is not any significant differences between two types of analysis. Similarly types of soil are not influence the distribution of axial force along the pier height.

5. Conclusions

The paper presents an efficient analytical procedure for materially and geometrically nonlinear finite element analysis of segmentally constructed highway bridge, including time dependent effects due to creep, shrinkage and aging of the concrete and the types of foundation soil. Komurhan Highway Bridge constructed with balanced cantilever method and located on the 51st km of Elazığ-Malatya highway is selected as an example. The P-Delta plus large displacement criterion is employed in the geometrical nonlinear analysis. The time dependent material properties, geometric variations and structure-soil interaction are included in investigation. From the results of this study, the following observations can be made:

- When the results of the construction stage analysis are compared to the one stage analysis, it is seen that there are large differences between displacements and some internal forces. It means that one stage analysis does not give the reliable and healthy solutions.
- Vertical deck displacements have increasing trend towards the middle of the bridge deck. In both analyses the maximum and minimum displacements occur on soft soil and without SSI situation, respectively. Types of soil have effect on deck vertical displacement.
- Bending moments of the bridge deck have a decreasing trend towards the middle of main span and increasing trend towards the connection point of pier and bridge deck. According to analysis types the influence of soil types is different. In one stage analysis the effect of soil types on bending moment of deck is too small. But when the time dependent material properties is taken into account on construction stage analysis the effect of soil types on bending moment of deck increase approximately 97% according to one stage analysis. Max. bending moment occurs on soft soil nevertheless min moment occur on without SSI situation.
- Types of soil foundation and analysis may not influence of some internal forces of bridges. The values of axial and shear force of deck and axial force of pier are approximately same in both foundation soil and analysis.
- To obtain real behavior of engineering structures, construction stage analysis using time dependent material properties, geometric variations and structure-soil interaction should take into account.

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