Finite Element Analysis for Obtaining Structural Performance of Bridge Pier Interacting with Soil

Mehmet Senturk[1] and Selim Pul[1]

[1] Karadeniz Technical University, Trabzon, Turkey

ABSTRACT: The purpose of this study is obtaining structural performance of a chosen reinforced concrete bridge pier, which is half-buried with soil, for different soil types. Another purpose of this study is exhibiting a finite element modelling approach for nonlinear behavior of reinforced concrete and soil under quasi-static loading. Within this scope, three-dimensional finite element push-over analyses under constant axial load and monotonically increasing top displacement were performed by using Abaqus/Explicit finite element solver. Plasticity and damage parameters and interaction between soil and structure were considered within the analyses. Concrete Damaged Plasticity (CDP), Drucker-Prager (DP) and Plastic material models in Abaqus were used for concrete, soil and reinforcement steel respectively. After analyses, it is observed that the structural parameters of pier such as bearing capacity, ductility, ultimate drift ratio and energy dissipation capacity of pier are dramatically varied depending on the soil types.

Keywords: Reinforced concrete bridge pier, finite element modelling, soil-structure interaction, nonlinear analysis, push-over analysis

1 INTRODUCTION

Bridges and viaducts are very important structures for civilizations. In case of natural disaster such as earthquake and flood, transportation must not be interrupted for better crisis management. For these reasons, new techniques and technologies for bridge construction are always needed.

Bridge piers are always exposed aggressive physical and chemical conditions. Structural health of bridge pier is always in danger because of different kind of potential threats such as collisions, landslides, floods, earthquakes etc. A viaduct pier buried with man-made soil fill example is given in Fig. 1. In this study, the effect of soil – structure interaction caused by filling around the pier on structural behavior of bridge pier were investigated. Three – dimensional finite element analyses were performed for a chosen bridge pier with two different soil type and half-buried soil filling level.

Bridge pier which was chosen for analysis is from an application project hence it satisfies code rules. It was designed according to Eurocode 8 (2005) and it also satisfies some minimum requirements of AASTHO LRFD (2012), Turkish Seismic Design Code (2007) and TS500 (2000) in some ways such as longitudinal reinforcement ratio and lateral reinforcement spacing in plastic hinge zone.

Figure 1. A viaduct pier buried with man-made soil fill example

In a study done by Kausel (2010) which survey static soil-structure interaction studies in the past, put forward that the history of soil-structure interaction phenomena is based on the late 18th century. It also says that it is a difficult multidisciplinary field that is mainly related to geotechnical and structural engineering.

It can be though that considering the soil-structure interaction by using correct material parameters within the analyses may improve the precision and reliability of results. However, Mylonakis and Gazetas (2000) mentioned that it may lead some critical unpredictable errors within the results because of indiscriminate inelastic behavior of soil. For this reason, it is thought that expectation about getting verified better results by using soil-structure interaction is not so feasible. Therefore, considering soil-structure interaction within the analyses can be used for getting some ideas about improvements of some situation related to geometry, materials and construction methods.

2 ANALYTICAL STUDY

2.1 Analysis Geometry

Cross-section of chosen bridge pier is given in Fig. 2. Cross-Section size is 1000 x 3500 mm. It includes 66 longitudinal bars with 26 mm diameter (66Ø26). Concrete cover is 75 mm from longitudinal bar's center to the outer face. The numbers of transverse reinforcement in a section is 3 ties and 11 cross-ties (Ties: 3Ø10/100/250 and Cross-ties: 11Ø10/100/250). Transverse reinforcement spacings are 100 mm and 250 mm for potential plastic hinge zone and above respectively. According to Eurocode 8 (2005), the potential plastic hinge length is assumed as 3500 mm which is the height of the cross-section. In addition, profile of pier is given in Fig. 3.

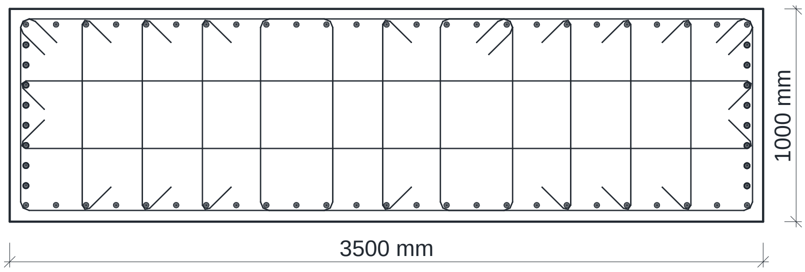


Figure 2. Cross-section of chosen bridge pier

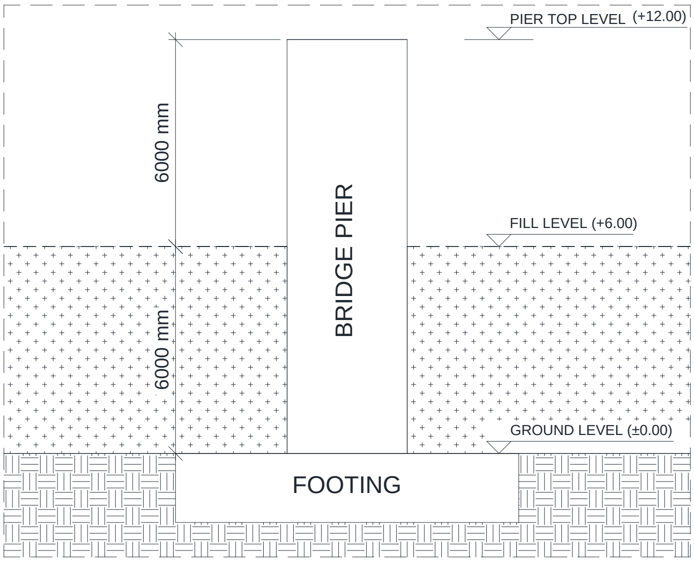


Figure 3. Profile of chosen bridge pier

2.2 *Finite Element Analysis*

In order to perform finite element analyses, Abaqus/Explicit software was used. It is suggested by Abaqus documentation (2014) to use explicit dynamic analysis technique for performing large scale non-linear quasi-static analysis with interaction. In addition, explicit dynamic technique considers inertia of mass within the analysis, hence loading protocol must be relatively slow to avoid inertia forces of mass for obtaining quasi-static structural behavior.

Within the analyses, concrete and soil materials were modeled as solid where both longitudinal and transverse reinforcement steels were modeled as wire. Brick finite elements were used for solid geometries and one-dimensional truss elements were used for wire geometries.

General contact was determined with separable frictional hard contact surface behavior for interaction between soil and structure. By using this kind of interaction surface behavior, it is possible to consider separations between interacting materials at tensile zones. Also, this approach may help to improve results due to regarding frictional forces parallel to interaction surface, however friction coefficients must be obtained carefully with laboratory tests. On the other hand, mesh convergence study was done to obtain best results within the interaction surfaces.

2.3 *Material Models*

2.3.1 Concrete material model

Concrete damaged plasticity (CDP) model was used for concrete material. Rodríguez et al. (2013) states that this model exhibits a good behavior under monotonic, cyclic and dynamic loading. Also, it includes a linear damage model with tensile cracking and compressive crushing modes. The model provides irreversible stiffness degradation related to irreversible tensile or compression damage which is occurred during the fracturing process.

Concrete model used in this study was calibrated using standard cylinder test in Abaqus. A cylinder with 150 mm dimeter and 300 mm height was tested under axial compression analysis by using Abaqus. Compression strength target was 30 MPa for standard cylinder. Non-linear concrete model parameters are given in Table 1.

Table 1. Concrete material model parameters

Concrete Damaged Plasticity Parameters							
Dilation Angle		**Eccentricity**		**f_{bo}/f_{co}**	**K**	**Viscosity Parameter**	
36°		0.1		1.16	0.667	0	
Compressive Behavior		**Compressive Damage**		**Tensile Behavior**		**Tensile Damage**	
Yield Stress (MPa)	**Inelastic Strain**	**Damage Parameters**	**Inelastic Strain**	**Yield Stress (MPa)**	**Cracking Strain**	**Damage Parameters**	**Cracking Strain**
15	0	0	0	3	0	0	0
23	0.0003	0.2	0.000333	2	0.0002	0.2	0.0002
29	0.00055	0.3	0.0007	1.5	0.0003	0.3	0.0003
33	0.00147	0.4	0.0013	1.2	0.0004	0.4	0.0004
25	0.0066	0.45	0.002	1	0.0005	0.5	0.0005
22	0.008	0.5	0.003	0.8	0.0008	0.6	0.0008
20	0.009	0.6	0.0043	0.5	0.001	0.7	0.001
10	0.01	0.8	0.007	0.4	0.002	0.8	0.002
		0.9	0.01	0.2	0.003	0.9	0.003
				0.1	0.005	0.99	0.005
Density (tonne/mm³)		**Young's Modulus (MPa)**			**Poisson Ratio**		
2.4×10^{-9}		28000			0.2		

2.3.2 Soil material model

Two different type of soil models were used to consider different type of fill. One of them is loose granular soil and other is dense cohesive soil. In order to simulate accurate soil behavior, Drucker-Prager plasticity model was used. Soil material parameters are given in Table 2.

Table 2. Soil material model parameters

Loose soil			**Dense soil**		
Density (tonne/mm³)	**Young's Modulus (MPa)**	**Poisson Ratio**	**Density (tonne/mm³)**	**Young's Modulus (MPa)**	**Poisson Ratio**
2×10^{-9}	124	0.3	2×10^{-9}	2068	0.25
Drucker-Prager Parameters			**Drucker-Prager Parameters**		
Angle of Friction	**Flow Stress Ratio**	**Dilation Angle**	**Angle of Friction**	**Flow Stress Ratio**	**Dilation Angle**
42°	1	0°	36°	1	0°
Yield Stress (MPa)	**Absolute Plastic Strain**		**Yield Stress (MPa)**	**Absolute Plastic Strain**	
0.075	0		0.48	0	
0.083	0.058		0.62	0.058	
0.075	0.116		0.48	0.116	

2.3.3 Reinforcement steel material model

For plasticity of reinforcement steel, "plastic" model which is built-in Abaqus was used. This model is suitable for ductile materials. In order to consider rupture of reinforcement steel, ductile damage parameters were integrated into the model. It is focused on that the material model with 420 MPa yield strength and 550 MPa ultimate strength. Plastic behavior of material was defined as bilinear. Non-linear steel material model parameters are given in Table 3.

Table 3. Reinforcement steel material model parameters

Density (tonne/mm^3)	Young's Modulus (MPa)	Poisson Ratio	Plastic Parameters	
7.8 x 10^{-9}	200000	0.3	**Yield Stress**	**Plastic Strain**
Ductile Damage Parameters			420	0
Fracture Strain	**Stress Triaxiality**	**Strain Rate**	420	0.0059
0.1	1	1	550	0.0979

2.4 Analysis Results

Three finite element analyses were performed under constant axial load and monotonically increasing top displacement in strong direction. Constant axial load level was chosen as 30% of axial load bearing capacity of pier. In order to calculate axial load bearing capacity, (f_{co} x A_g) formula is used where f_{co} is standard cylinder strength of concrete and A_g is gross area of cross-section of bridge pier. One of the analysis is reference which has no filling. Other models have six meters soil fill with two different type of soils. Analysis results are given in Fig. 4.

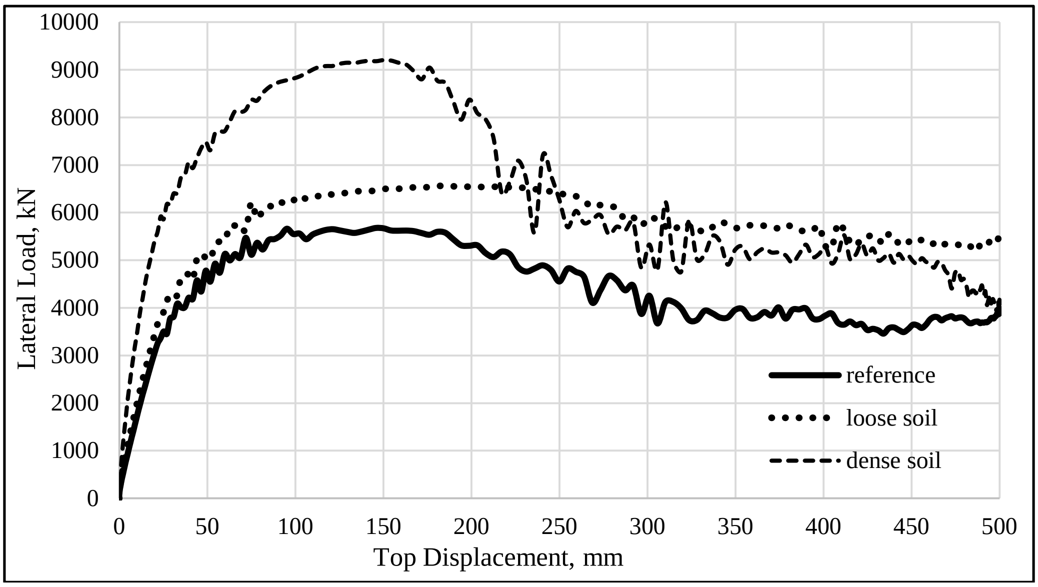


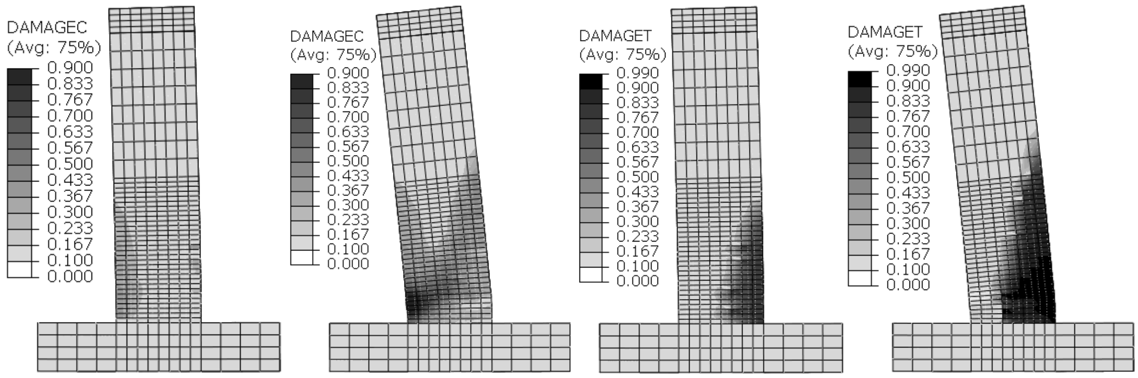
Figure 4. Analysis results

In order to determine yield point, equivalent elasto-plastic energy absorption approach given Park (1989) was used. Ultimate displacements of piers were determined based on significant bearing capacity after peak approach given with Park (1989). A software developed using Matlab programming language was used to calculate lateral load bearing capacity, top displacement at yield and ultimate and ductility ratio of piers. These are given in Table 4.

Table 4. Structural properties of piers

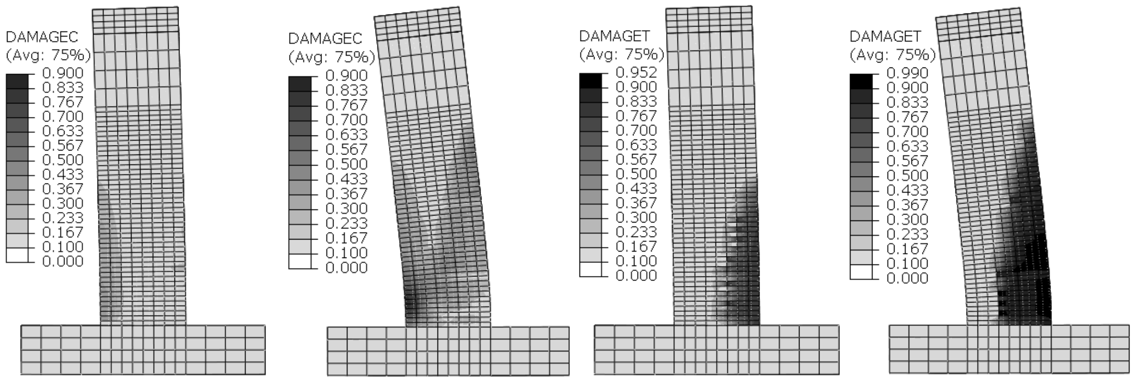
Model Name	Lateral Load Bearing Capacity (kN)	Top Displacement at Yield (mm)	Top Displacement at Ultimate (mm)	Ductility Ratio
Reference (No fill)	5680.51	53.18	226.54	4.26
Loose Soil Fill	6565.30	59.55	428.43	7.19
Dense Soil Fill	9203.38	51.48	213.72	4.15

Compression and tension damage patterns at yield and 2% drift ratio for reference, loose soil and dense soil model are given in Fig. 5, Fig. 6 and Fig. 7 respectively. Plus, calculated cumulative energy dissipation curves are given in Fig. 8.



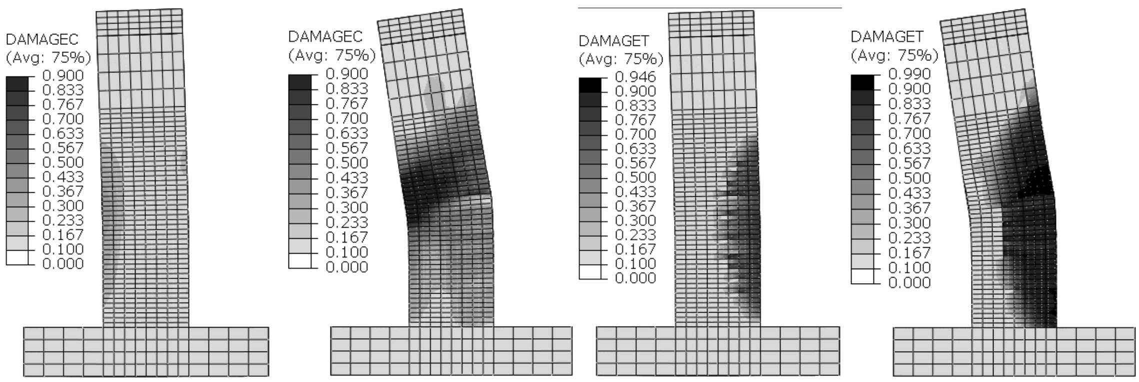
(a) Compression damage at yield (b) Compression damage at 2% drift ratio (c) Tension damage at yield (d) Tension damage at 2% drift ratio

Figure 5. Concrete compression and tension damage pattern for reference model (scale factor = 5)



(a) Compression damage at yield (b) Compression damage at 2% drift ratio (c) Tension damage at yield (d) Tension damage at 2% drift ratio

Figure 6. Concrete compression and tension damage pattern for loose soil model (scale factor = 5)



(a) Compression damage at yield (b) Compression damage at 2% drift ratio (c) Tension damage at yield (d) Tension damage at 2% drift ratio

Figure 7. Concrete compression and tension damage pattern for dense soil model (scale factor = 5)

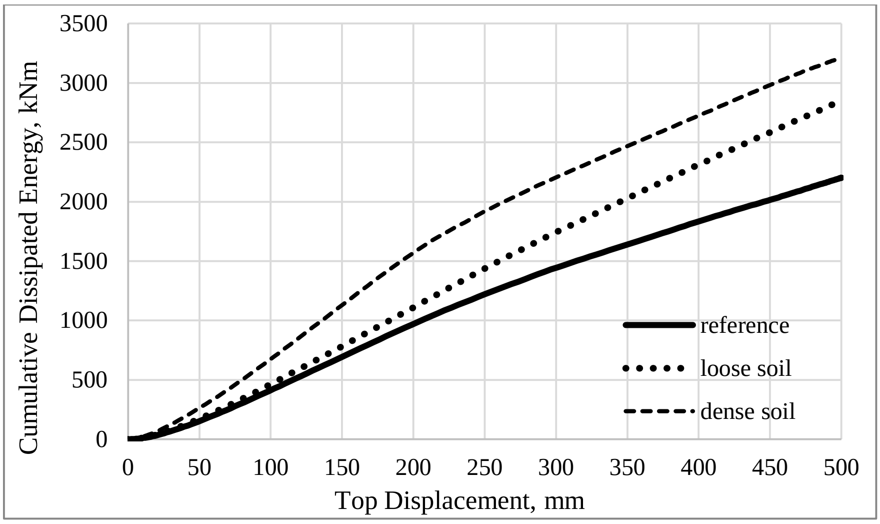


Figure 8. Cumulative dissipated energy

3 DISCUSSION

Analysis results showed that filling the bridge pier with soil may help to improve its quasi-static structural performance. Not only bearing capacity of pier but also ductility and energy absorption capacity may be enhanced through soil fill. It is shown that in case of dense soil, enhancement of lateral load bearing capacity of pier is higher but ductility is lesser. In contrast, when the filling soil is loose granular soil, ductility may be increased significantly and also lateral load bearing capacity may be increased a little. Similarly, soil type affect initial stiffness of pier directly.

In a different scope, it is quite possible to have further advantageous and/or disadvantageous by using soil fill in case of seismic loading. Soil fill might behave like damper with its elasticity and mass. Also, it might absorb a big amount of earthquake energy. On the other hand, because of fast loading seismic behavior of loose soil might evolve to dense soil. Therefore, in seismic loading case, soil fill might provide extra lateral load bearing capacity but reduce ductility.

4 RESULTS

Results obtained from this study are summarized below.

- Soil fill can be used for enhancing structural performance of bridge piers.
- Soil fill with loose soil may delay significant structural damage in bridge pier due to its damper-like behavior.
- Man-made or natural filling not considered in design process must be taken under control for some unexpected structural behavior changes.
- Changing of initial stiffness of bridge pier through dense soil fill may cause some other problem such as altering the vibration characteristics of pier. This situation may affect seismic response of pier negatively.
- Seismic behavior of soil filled bridge pier is out of this study. However, it is suggested to research seismic behavior of soil fill with appropriate finite element analysis techniques. Then it may be possible to use soil fill for structural improvement.

5 REFERENCES

AASHTO, L. 2012. *Bridge Design Specifications*. American Association of State Highway and Transportation Officials, Washington. DC, USA

Abaqus, V. 2014. 6.14 *Documentation*. Dassault Systemes Simulia Corporation.

Eurocode 8. 2005. *Design of Structures for Earthquake Resistance–Part 2: Bridges*. European Committee for Standardization, Brussels, Belgium

Kausel, E. 2010. *Early history of soil–structure interaction*. Soil Dynamics and Earthquake Engineering, 30(9), 822-832.

Matlab R2016a, The MathWorks, Inc., Natick, Massachusetts, United States.

Mylonakis, G, and Gazetas, G. 2000. S*eismic Soil-Structure Interaction: Beneficial or Detrimental?* Journal of Earthquake Engineering, 4(03), 277-301.

Park, R. 1989. *Evaluation of Ductility of Structures and Structural Assemblages from Laboratory Testing*. Bulletin of the New Zealand National Society for Earthquake Engineering, 22(3), 155-166.

Rodríguez Soler, J, Martinez Cutillas, FJ, and Marti Rodriguez, J 2013. *Concrete Constitutive Model, Calibration and Applications*. 2013 SIMULIA Community Conference

Specification for Buildings to be Built in Seismic Zones, 2007, General Directorate of Natural Disasters, Ankara, Turkey

TS500, 2000. *Requirements for design and construction of reinforced concrete structures*, Turkish Standards Institution, Ankara, Turkey.