Dynamic Analysis of Buried Pipelines with Geogrid Reinforcement

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ABSTRACT: In this study, numerical analyses on interaction between a high density polyethylene (HDPE) pipeline and a loose and dense sand reinforced with a geogrid layer was performed in PLAXIS 2D, a software program run by finite element method (FEM). The diameter and thickness of the pipeline were chosen as 400 mm and 12 mm respectively. The pipeline was constructed in a trench with fill material in sandy soil. The center of the pipeline was located 1.40 m below the ground surface. The pipeline was analyzed under the effect of Kobe earthquake, which could be assumed as a real damaging seismic hazard. Vertical and horizontal displacement and strain values of the pipeline were compared for two different cases. For the first case, the pipeline was placed in sand without any geogrid reinforcement; for the second case, a geogrid layer was placed 20 cm above the pipeline crown. According to the results of the numerical analyses, the displacements obtained on the pipeline were lowered by placing geogrid above the pipeline. However, significant displacements which could give destructive damage to the pipeline were obtained in both dense and loose sand. Although geogrid reinforcement lowered the displacements, the pipeline could still be damaged. Maximum vertical displacement was measured higher than maximum horizontal displacement in loose sand whereas maximum horizontal displacement was higher than maximum vertical displacement in dense sand. Furthermore, vertical strain caused compression on the pipeline with geogrid reinforcement but extension without geogrid reinforcement.

Keywords: Pipeline, Finite Element Method, Geogrid, Dynamic Analysis

1 INTRODUCTION

A buried pipeline is a cylindrical material, usually manufactured from steel, polyvinyl chloride (PVC) or high density polyethylene (HDPE) that is generally used to transport water, sewage, oil and natural gas (O’Rourke and Liu, 1999). The earthquake safety of buried pipelines has become a significant case in recent years. Pipelines buried under the ground generally cover large areas and are subject to geotechnical hazards.

Buried pipelines might be damaged either by permanent ground deformation (PGD) or by transient seismic wave propagation (O’Rourke and Liu, 1999). Substantial pipeline damages were recorded in past major earthquakes, such as 1906 San Fransisco, 1933 Long Beach, 1952 and 1954 Kern County, 1964 Nigata, 1971 San Fernando, 1979 Imperial Valley, 1989 Loma Prieta, 1994 Northridge, 1999 Duzce and 1999 Chi Chi Earthquakes (O’Rourke and

Lane, 1989; O'Rourke and Palmer, 1996; Tang, 2000). O'Rourke and Liu (1999) suggested that PGD hazards were usually limited to small regions and their potential for damage was very high since they could impose large deformation on pipelines. However, the wave propagation hazards typically affect the whole pipeline network, but with lower damage rates. PGD is generally observed during surface faulting, land sliding, seismic settlement and lateral spreading due to soil liquefaction. O'Rourke and Liu (2012) stated that buried pipeline damages were generally much more likely to occur by ground deformation than by seismic wave.
Finite Element Method (FEM) is one of the most reliable analyses for seismic response of buried pipelines. Investigating geotechnical problems using FEM has been widely used in this research area for many years although there are limitations for analyzing such problems accurately. However, linear and nonlinear problems such as prediction of settlement and deformation between buried pipelines and soil are preferred to be solved by FEM (Cameron, 2005). For this reason, the software program PLAXIS is usually chosen in order to estimate failure aspects of buried pipelines.

A geogrid is a geosynthetic material that is often used as a reinforcement layer in embankments or soil retaining structures. The geogrid can also be placed in soil above buried pipelines in order to improve the bearing capacity and spread the loaded area. Geogrid can carry substantial tensile stresses and tends to deform considerably under relatively small stresses (Rajkumar and Ilamparuthi, 2008). Geogrid can be simulated in PLAXIS by the use of tension elements combined with interfaces in order to model the interactions with the surrounding soil (Cameron, 2005). In literature, either numerical analyses with FEM or laboratory experiments related to buried pipelines in soil reinforced with geogrid, were performed in static conditions. Cameron (2005) conducted FEM analyses in PLAXIS 2D by using PVC pipelines in loose and dense sand reinforced with a single geogrid layer placed 10 cm and 20 cm above the pipe crown respectively. According to the results, vertical displacements of the pipeline were significantly lowered by geogrid reinforcement. Similar results were obtained from the laboratory tests conducted on PVC pipelines in loose and dense sand reinforced with a geogrid layer that was placed 20 cm above the pipe crown (Rajkumar and Ilamparuthi, 2008). Test results indicated that geogrid reinforcement caused a significant reduction in the crown deflection of the pipe when the pipeline was subjected to surface pressures. In another study, Armaghany et al. (2014) performed a numerical analysis in PLAXIS 3D in order to investigate the effect of geogrid placement above a steel pipeline buried in loose sand on the uplift resistance of the pipeline. According to the results, placing geogrid above the pipeline improved the uplift resistance.

2 NUMERICAL STUDY

The objective of this study was to analyze the displacements and strains occured on a HDPE pipeline buried in both loose and dense sand under the effect of Kobe Earthquake. Furthermore, the results were compared with those obtained when placing a geogrid layer above the pipeline in the sand. The dynamic analyses were performed by using FEM in PLAXIS 2D.

2.1 *Materials*

The HDPE pipe used in FEM was selected as a tunnel element composed of a plate material buried in sand. The soil was chosen as loose and dense sand. First, a trench was provided in the sand for placing the pipe. Then, the fill material was placed in the trench. The fill material was selected as a soft material in the loose sand and as a stiff material in the dense sand. Engineering parameters for loose sand, dense sand, soft fill and dense fill were listed in Table 1 (Brinkgreve et al., 2010). Dimensions of the numerical model was taken as 10mx10m in PLAXIS 2D. The pipe was buried in the trench with 2 m width at the surface and 1 m width at the bottom. The height of the trench was taken as 2 m. Diameter and thickness of the pipe was selected as 400 mm and 12 mm respectively. The center of the pipe was buried 1.80 m below the surface. The geogrid layer was placed 1.40 m below the surface and 20 cm above the pipe crown. Engineering parameters for the pipe and geogrid layer were listed in Table 2.

Table 1. Engineering Parameters for Soil and Fill Material

SYMBOL	EXPLANATION	LOOSE SAND	DENSE SAND	SOFT FILL	STIFF FILL
γ_{unsat}	Unit Weight	16	19	14	16
γ_{sat}	Saturated Unit Weight	19.4	20.6	18	19.4
E_{50}^{ref}	Secant stiffness in standard drained triaxial	15000	60000	10000	15000
E_{oed}^{ref}	Tangent stiffness for primary oedometer loading	15000	60000	10000	15000
E_{ur}^{ref}	Unloading / reloading stiffness	45000	180000	30000	45000
m	Power for stress-level dependency of stiff-ness	0.622	0.387	0.65	0.622
C'_{ref}	Cohesion	1.0	1.0	1.0	1.0
φ	Friction angle	31	40.5	25	31
Ψ	Dilatancy angle	1	10.5	0	1
R_f	Failure ratio	0.969	0.875	.99	0.969
$\gamma_{0.7}$	Shear strain at which G_s=0.722G_0	1.8E-4	1E-4	1.8E-4	1.8E-4
G_o	Shear modulus at very small strains	77000	128000	40000	77000
ν_{ur}	Poisson's ratio	0.2	0.2	0.2	0.2

Table 2. Engineering Parameters for Pipe and Geogrid

MATERIAL	PIPE (HDPE)	GEOGRID
EA (kN/m)	4560	60
EI (kN.m^2/m)	460	-
D (m)	0.4	-

2.2 *Modelling in FEM*

Dynamic analyses were performed in PLAXIS 2D by using hardening soil model with small strain stiffness (HS small). This model was selected because HS small model is the most reliable model available in PLAXIS 2D for cycling loading calculations in order to obtain reasonable results whereas other models were only expected to give crude approximations. This model could be applied to both cohesionless and cohesive soils and it could take hysteretic damping into account (Laera and Brinkgreve, 2015; Brinkgreve et al., 2007).

Vertical boundaries were selected as viscous whereas the bottom horizontal boundary was chosen as a constraint base. 6 nodal triangle elements were used for mesh generation and the elements surrounding the pipe were considered very fine to raise modelling accuracy.

Calculation steps were divided by three phases: Initial phase, plastic phase and dynamic phase. In initial phase, geometry of the model was provided and the soils were taken into account without using the pipe and the geogrid. Then, the plastic phase was considered as a static analysis by taking the pipe, geogrid and interfaces around these materials into account. Finally, the dynamic phase was run by considering the earthquake loads. In the dynamic analysis, prescribed displacement along x-axis was introduced in order to apply the desired earthquake motions. The sandy soil, fill material, buried pipeline, geogrid placed above the pipeline and the prescribed horizontal displacement were shown in PLAXIS 2D in Figure 1.

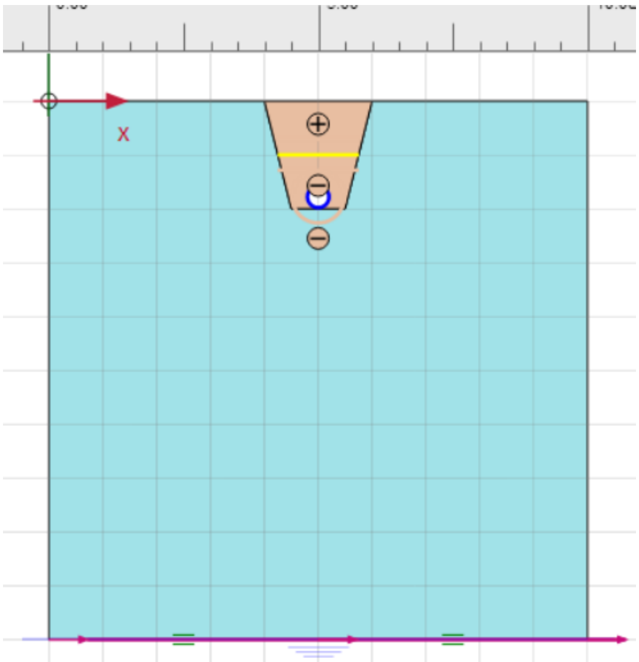

Figure 1: Pipeline Model inside the Trench in Sand

After generating the mesh, the triangular elements around the pipe and the geogrid were given in Figure 2. The critical point C that was located at the middle of the right edge of the circular cross-section of the pipeline was also shown in Figure 2. In order to evaluate the effect of the earthquake, behavior of the pipeline in terms of movement and deflection would be crucial. For this reason, the vertical and horizontal displacement and strain values of point C were obtained after the termination of the dynamic calculations.

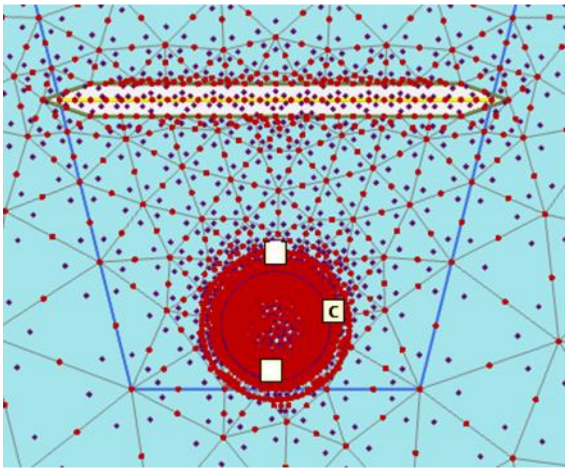

Figure 2: Mesh Generation and Point C on the Pipeline

Kobe Earthquake was selected as the dynamic motion acting on the pipeline. The seismic parameters of Kobe Earthquake were transferred into the dynamic analyses performed in PLAXIS 2D. Peak ground acceleration (PGA) of Kobe Earthquake was measured as 0.82g. Acceleration, velocity and displacement-time histories of Kobe Earthquake were shown in Figure 3. The elapsed time for this earthquake was taken as 48 sec.

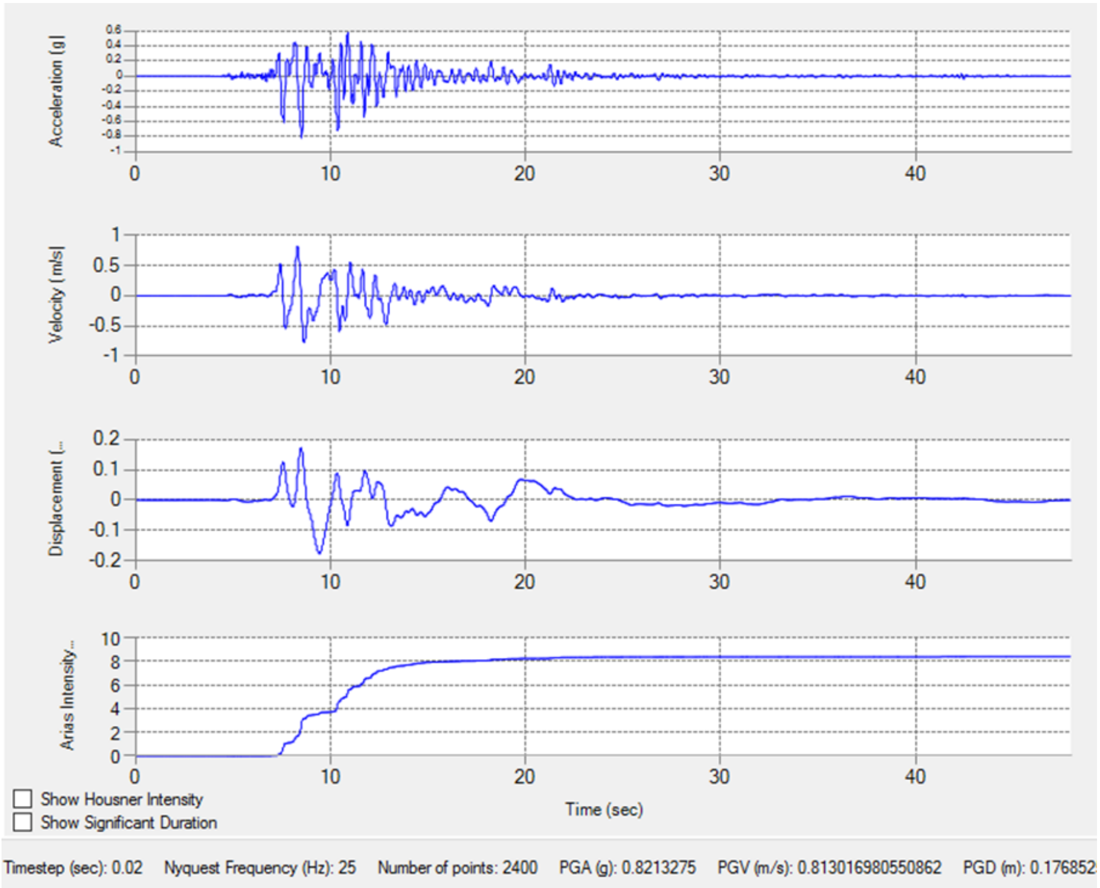

Figure 3: Acceleration, Velocity, Displacement-Time Histories of Kobe Earthquake

3 RESULTS

After the calculations in PLAXIS 2D were completed, output data in terms of displacement and strain of point C versus time were taken. Vertical displacement of the pipe could be evaluated as one of the most significant parameters related to the failure of the pipe. Maximum allowable displacement values in cohesionless soils were limited to 4 cm (ASCE, 2001). When the measured displacement of the pipeline was higher than 4 cm, then, it would mean that the pipeline had encountered safety problems or even failure had occured.

In this study, vertical displacement of point C on the pipeline in loose sand and dense sand versus time graphs were shown in Figure 4 and Figure 5 respectively. For all of the displacement and strain graphs, both the case with geogrid placement and the case without any reinforcement were shown.

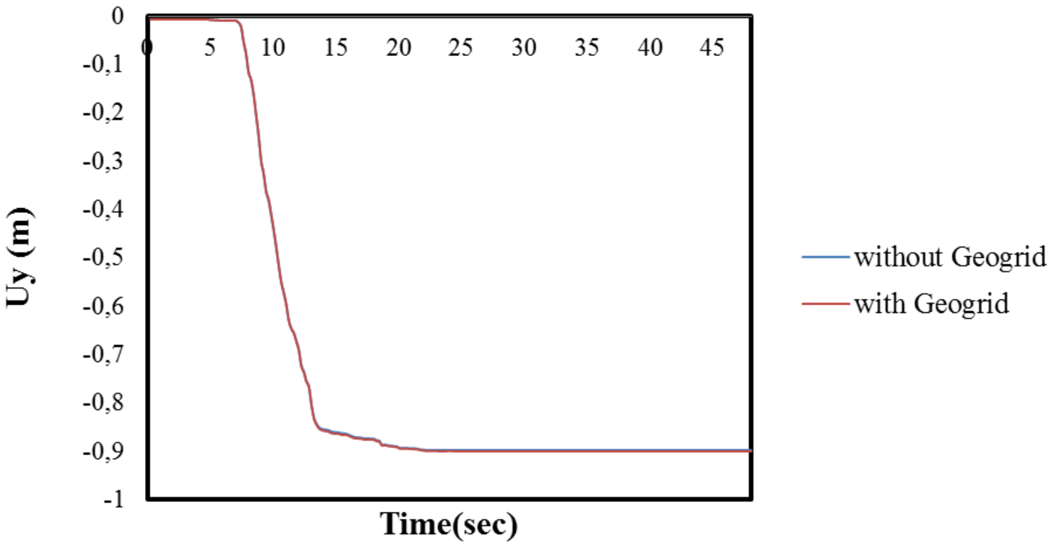

Figure 4: Vertical Displacement of Point C-Time in Loose Sand

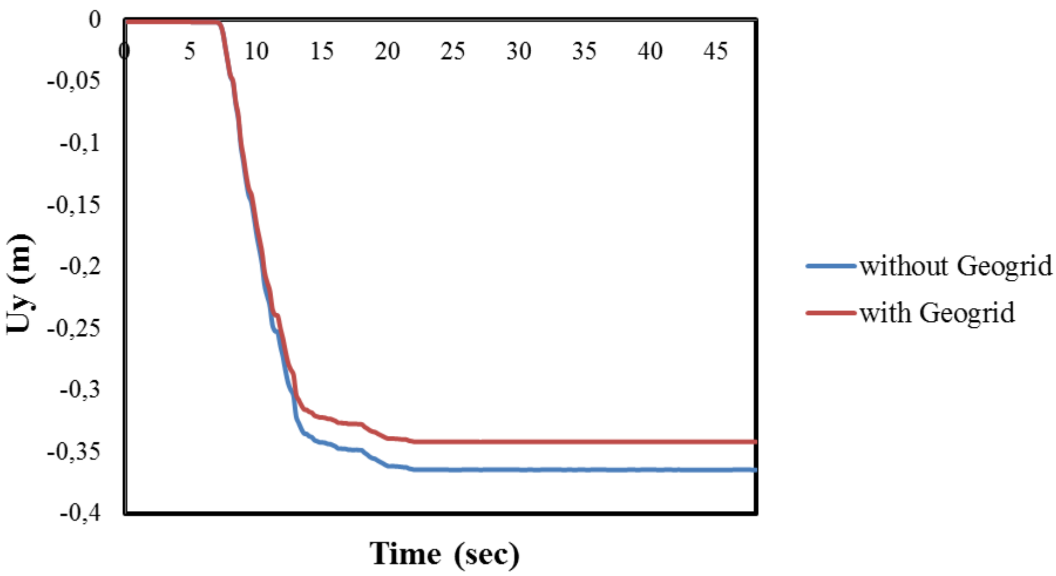

Figure 5: Vertical Displacement of Point C-Time in Dense Sand

As can be seen in Figure 4 and Figure 5, displacement of the pipeline was higher in loose sand than in dense sand. In loose sand, point C moved almost 90 cm for both cases where geogrid was placed above the pipe and not. However, pipeline displacement was measured as approximately 37 cm without geogrid and 34 cm with geogrid placement in dense sand. As shown in Figure 5, geogrid placement above the pipe, lowered the displacement of the pipe very slightly. Furthermore, all of these displacement values were much higher than the upper limit of the allowable displacement in sand.

Horizontal displacements of the pipeline were also calculated and shown in Figure 6 and Figure 7 for loose sand and dense sand respectively. As the earthquake load acted horizontally on the pipe, the horizontal displacements were expected to be similar with the behavior of the acceleration-time history of Kobe Earthquake.

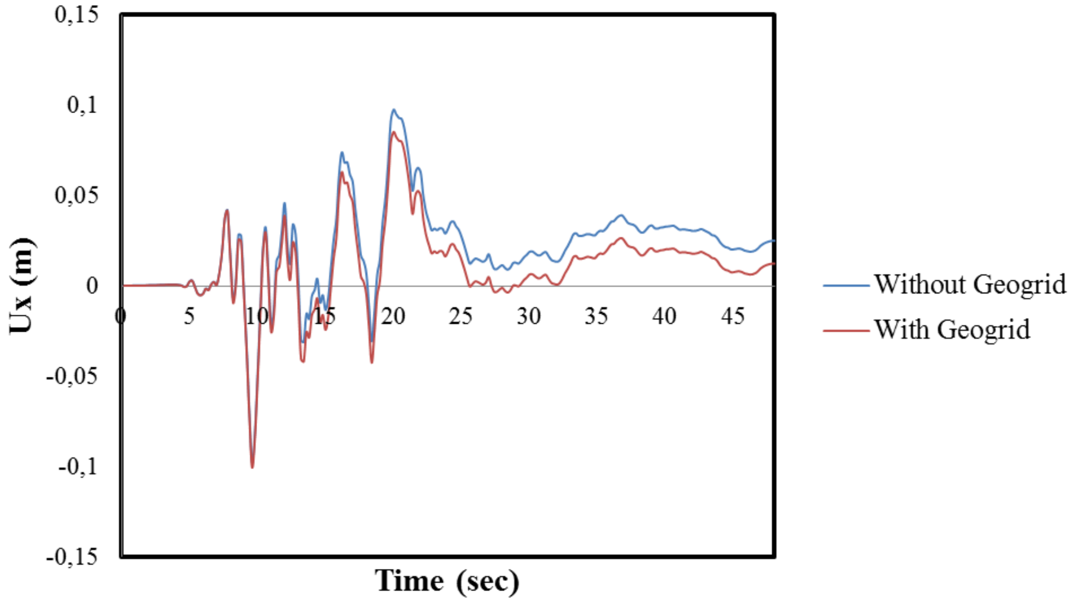

Figure 6: Horizontal Displacement of Point C-Time in Loose Sand

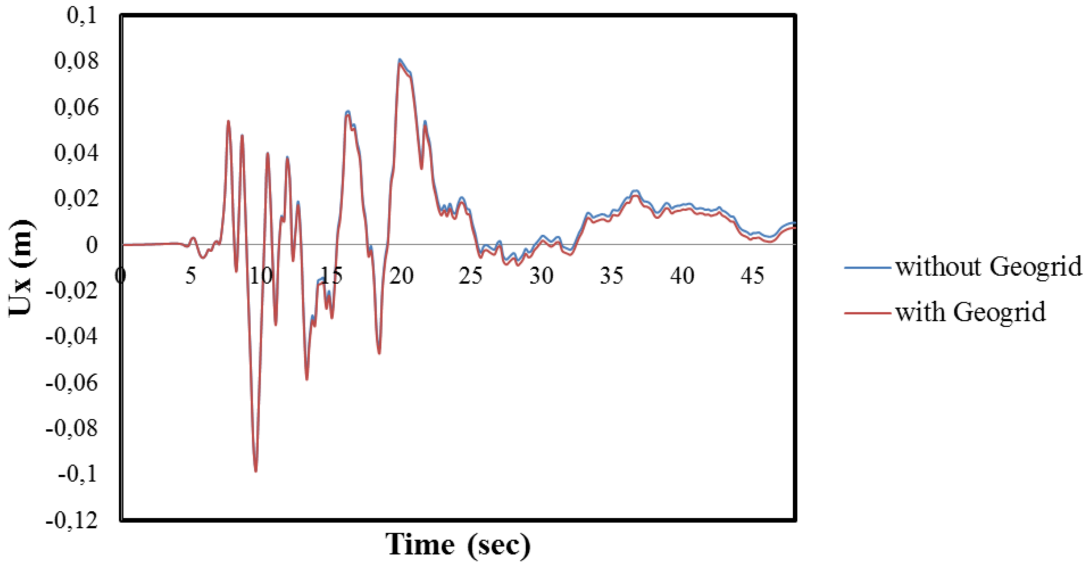

Figure 7: Horizontal Displacement of Point C-Time in Dense Sand

As shown in Figure 6, the maximum horizontal displacement of the pipe was measured as approximately 10 cm in loose sand in 48-seconds. This parameter was obtained as almost the same when the pipeline was buried in dense sand as can be seen in Figure 7. However, geogrid placement above the pipe caused again a slight decrease in horizontal displacement both in loose sand and dense sand.

The principal failure modes for buried pipelines are rupture due to axial tension and local buckling due to axial compression. Tensile failure occurs due to excessive axial tension along the buried pipeline and local buckling occurs because of excess axial compression (O'Rourke and Liu, 1999). The strain associated with tensile failure is generally about 4% (Newmark and Hall, 1975) whereas suggested allowable maximum strain for HDPE pipelines is 1%.

Either vertical or horizontal strain of the pipeline could indicate the deflection occurred on the pipe under the effect of the acting earthquake. Vertical strain values obtained in loose sand and dense sand were shown in Figure 8 and Figure 9 respectively. In loose sand, maximum vertical strain was obtained as almost 35% without geogrid reinforcement whereas -25% with geogrid reinforcement. In dense sand, these values were measured as approximately 4% and -9% respectively. According to the results, vertical deflection of the pipe could be assumed to be extension without geogrid but compression with geogrid placement in both loose sand and dense sand as can be seen in Figure 8 and 9. Vertical strain values in loose sand were extremely high when compared to those in dense sand. However, all of these strain values were much higher than the maximum limit value given in the literature.

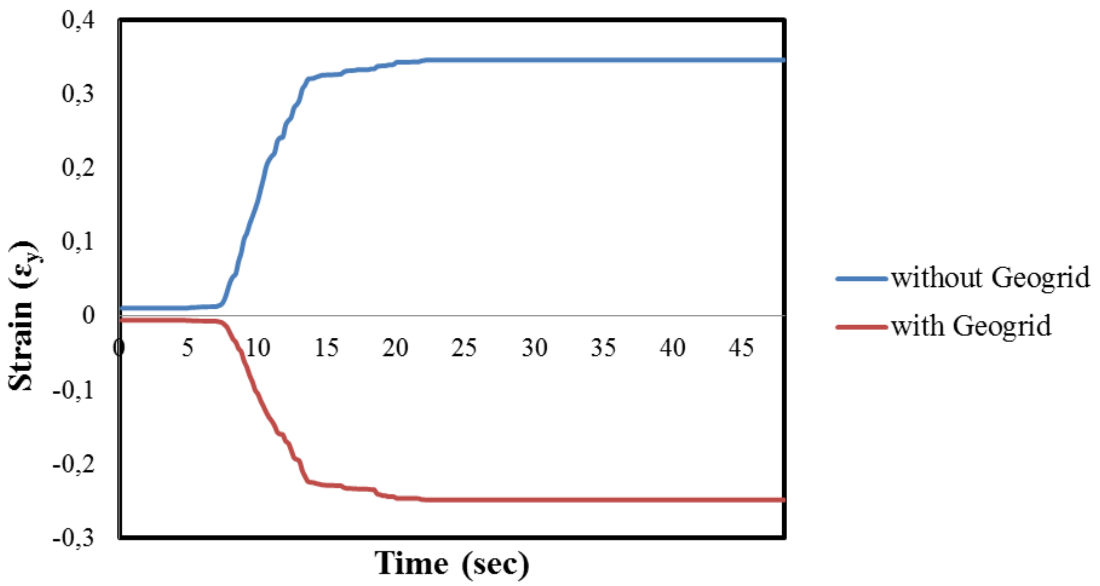

Figure 8: Vertical Strain of Point C-Time in Loose Sand

Different strain behavior was observed for horizontal strain-time graph for the pipeline tested in loose sand as shown in Figure 10. The maximum horizontal strain was measured as approximately 25% with geogrid reinforcement whereas -30% without geogrid reinforcement. Geogrid placement resulted in tensional horizontal deflection, however, compression was obtained without geogrid placement as can be seen in Figure 10. Horizontal strain values were lower in dense sand than those obtained in loose sand. However, only extensional deflection was observed for both with and without geogrid placement. The maximum horizontal strain was approximately 12% and 5% when geogrid was placed above the pipe and not respectively.

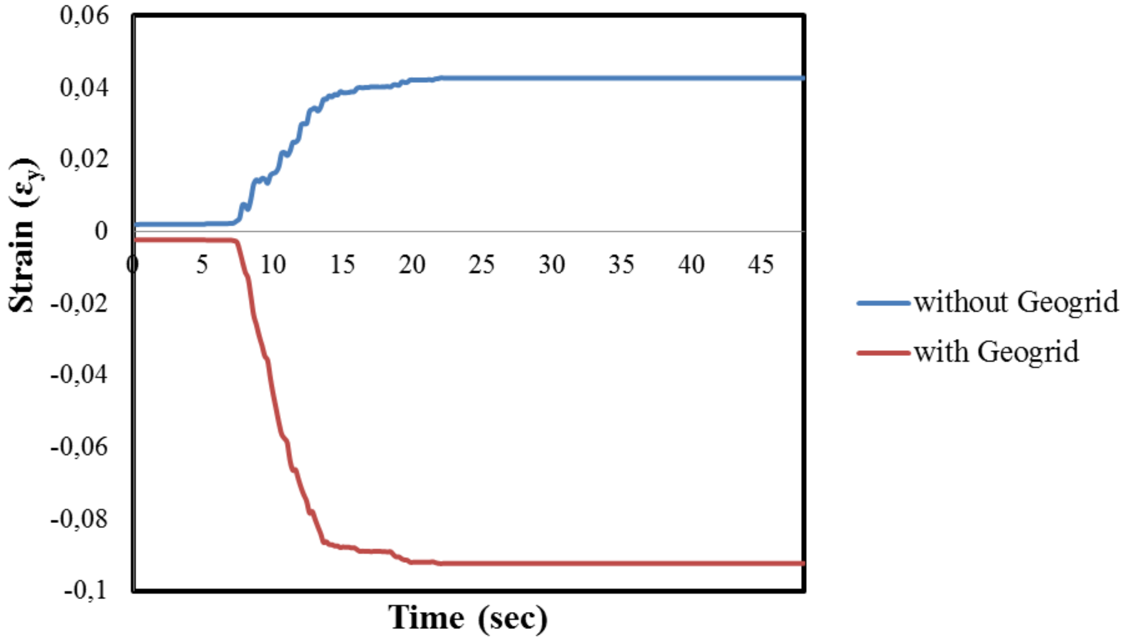

Figure 9: Vertical Strain of Point C-Time in Dense Sand

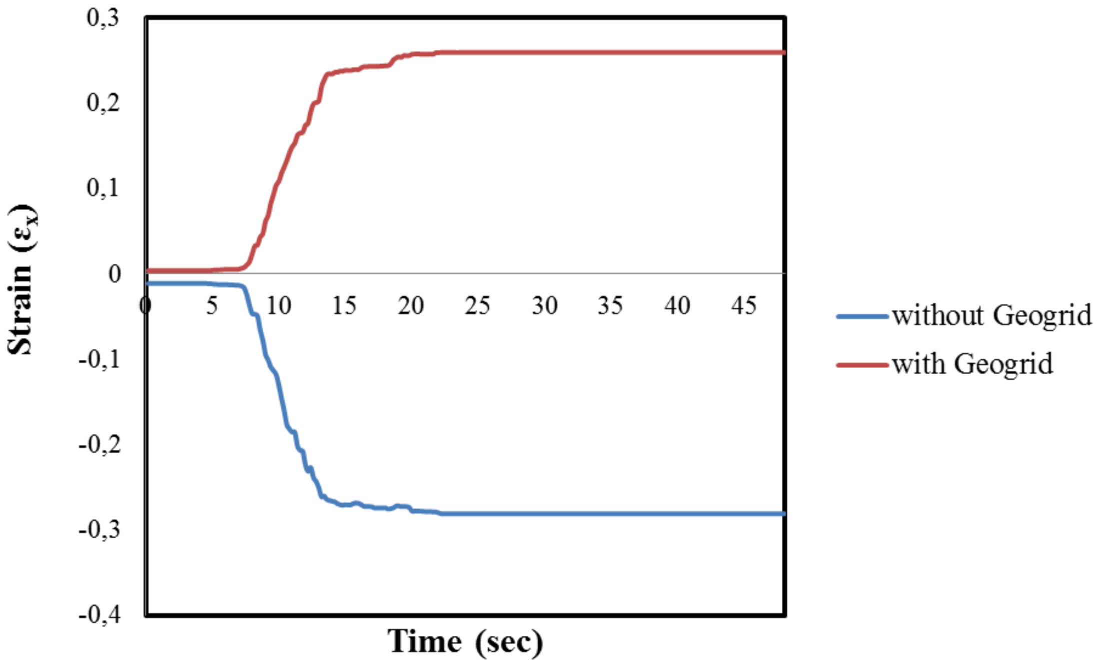

Figure 10: Horizontal Strain of Point C-Time in Loose Sand

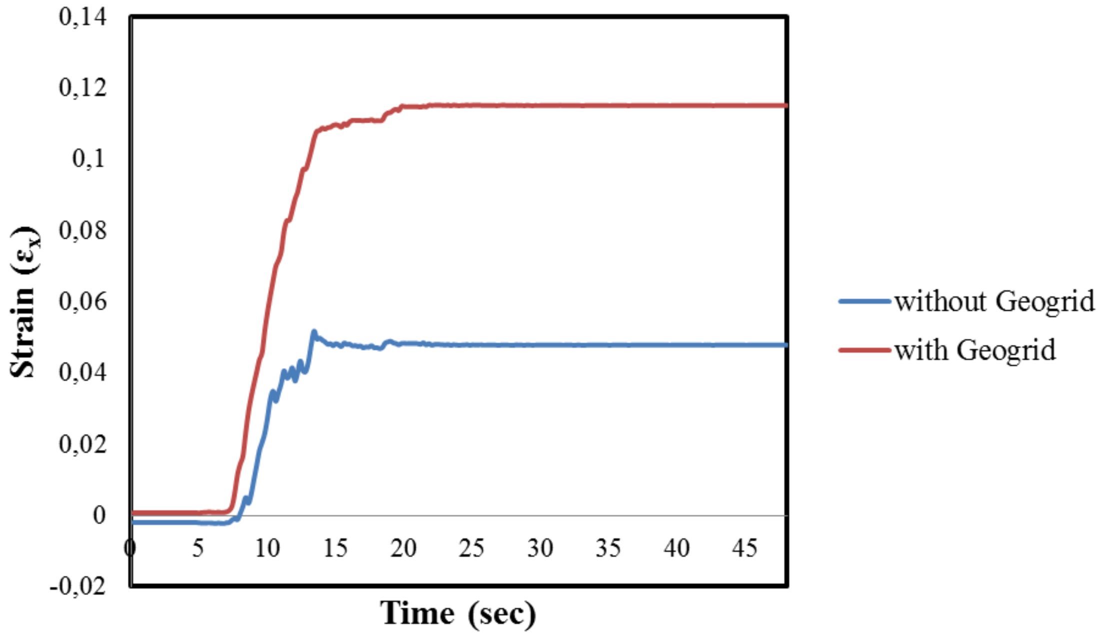

Figure 11: Horizontal Strain of Point C-Time in Dense Sand

4 DISCUSSION AND CONCLUSIONS

Based upon the obtained results of the dynamic analyses, pipeline displacements were greater than the limited values given in the literature. Vertical displacements, that were the most critical ones, were even higher than the horizontal displacements. According to these displacements, failure of the pipeline in sand could possibly occur under the effect of Kobe Earthquake.

Geogrid placement 20 cm above the pipe caused only a few centimeters decrease in vertical displacements.

Vertical displacements measured on the pipeline were much higher in loose sand than in dense sand. This behavior could be attributed to the lower relative density of loose sand. Due to this lower relative density, the interlocking of the sand particles would be low, which might have resulted in high movements under the effect of peak ground accelerations.

Geogrid placement above the pipeline was found to be more effective in loose sand when compared to that in dense sand.

Vertical strain values obtained on the pipeline in loose sand were incredibly high both with and without geogrid reinforcement. Along vertical direction, pipeline was elongated when no geogrid was used both in loose and dense sand; however, pipeline was compressed when geogrid was placed above the pipe both in loose and dense sand. According to these results, geogrid layer placed above the pipeline migh have exerted opposite reaction towards the pipeline under the effect of Kobe Earthquake, that might have caused the contraction of the pipeline.

Along horizontal direction, very high strain values were obtained on the pipeline again. Pipeline was compressed when geogrid was not placed above the pipe whereas pipeline was elongated when geogrid was placed above the pipe in loose sand. However, only elongation was obtained on the pipeline in dense sand for both cases, with and without geogrid reinforcement. Based upon these results, failure might have occured along vertical direction due to rupture when geogrid was not used in both loose and dense sand and due to local buckling when geogrid was placed 20 cm above the pipe. However, rupture might have occured along horizontal direction for both cases with and without geogrid in dense sand and for the case with geogrid in loose sand. Local buckling could be the reason for failure along horizontal direction when geogrid was not used in loose sand (O'Rourke and Liu, 1999).

As a conclusion, although geogrid placement 20 cm above the buried pipeline in sand decreased pipeline displacements under the dynamic effect of Kobe Earthquake, its contribution to pipeline stability could not be as crucial as that in static case.

Even if we may derive significant results from the displacement values of the pipeline used in sand, we cannot predict very clear and definite conclusions from the strain values of the pipeline. Further research has to be conducted on buried pipelines reinforced with geogrid and subjected to hazardous dynamic loads both numerically and experimentally.

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