Response analysis of buried pipeline subjected to earthquake faulting: A DEM and FEM simulation

Md. Aftabur RAHMAN* & Hisashi TANIYAMA**

*Graduate student, Department of Civil and Environmental Engineering, Saitama University, Japan; Email: aftabur028@yahoo.com
**Faculty member, Department of Civil and Environmental Engineering, Saitama University, Japan; Email: taniyama@mail.saitama-u.ac.jp

ABSTRACT

Seismic action is entirely different in buried pipe system than other types of structures. The major cause of damage to buried pipeline during an earthquake is owing to ground deformation when crossing an active fault. A 3D Distinct Element Method (DEM) analysis is carried out to examine the response of buried pipeline when subjected to fault movement. Spherical particles are considered to represent the soil behavior and DEM simulation has been performed for the soil particles. After that strike-slip fault movement is given to the model. Pipe is considered as a beam element and fixed boundary conditions are specified for compatibility of the analysis. Response of the pipes has been calculated using 3D FEM. Dynamic behavior of particles and pipes has also been well thought-out in the analysis. The relationship between resultant force of pipes and particles and displacement of pipes at each nodal point has been outlined. It is observed that particles pushes pipes near the fault crossing point and causes axial deformation in the pipe elements with the increment of fault slip. The soil-pipe interaction is somewhat understandable from the force-displacement relation of pipes at each nodal point. Strain in longitudinal axis of the pipes has been observed through the numerical simulation. Strain rate with the increment of fault movement has also been analyzed.

Keywords: Buried pipe, Discrete element method, Fault displacement, Strain, Force-displacement relation.

1. INTRODUCTION

Buried pipe existed in prehistory when caves were protective habitat, and ganats (tunnels back under mountains) were dug for water. The value of pipes is found in life forms. Now a day's buried pipeline are commonly used to transport oil, water, sewage and natural gas. These pipelines are sometimes referred to lifeline systems as they are essential for the support of life and maintenance of property. Underground pipeline in high seismic zones are subjected to permanent ground deformation and wave propagation hazards. In buried pipe, seismic action is not same as the above ground structures. Inertia force is the critical factor for above ground structures whereas in underground pipe system ground rupture due to fault movement, seismic wave propagation, liquefaction is the most important factors (Datta; 1999) .

The heaviest damage to underground water pipes occurred between firm ground at hillside and soft ground in down-town district in 1923 Kanto earthquake. It was reported that after the Kobe earthquake in 1995 in Japan, gas leakage from buried pipeline occurred at 234 different places and fires started due to gas release and burnt over one square kilometer area (EQE report;1995). However, Chi-Chi earthquake in Taiwan in 1999 have caused severe damage to buried pipelines (Wang; 2003).

Seismic response analysis of buried pipes is a complex phenomenon including three dimensional dynamic analysis of soil-structure system. Soil-pipe interaction is a complex criterion for the analysis of buried pipe. The ground movements of active faults have the most severe earthquake effects on buried pipelines. A rigorous analysis satisfying all the conditions is difficult; hence degrees of simplifications are made to obtain a good estimate of the response quantities of interest.

Different types of modeling of buried pipes subjected to fault movements are available starting from extremely simple to complex three dimensional modeling. Newmark and Hall (1975) was pioneer in the field and developed a simplified analytical techniques for the pipeline subjected to fault movement. They related the soil slip friction on the pipe to the earth pressure at rest and the pipe elongation was calculated using the small deflection theory. This method was based on the assumption that the pipe is placed in a trench with shallow slopping sides so that it can accommodate itself to the transverse as well as the longitudinal components of fault displacement in part by moving out of trench. Their method was extended by Kennedy et al (1977) incorporating bending of the pipeline near the fault crossing point and considering the soil lateral forces. Wang and Yeh (1985) proposed a refined analysis procedure for calculating the elongation of buried pipeline subjected to strike slip faulting or reverse faulting using large deflection theory. The method proposed by Newmark, Kennedy and Wang did not consider the section deformation of pipe. Takada et al (2001) proposed a simplified method for obtaining the maximum strain in steel pipes considering non-linearity of material and geometry of pipe section when crossing an active fault. Karamitros et al **(**2007) proposed an analytical methodology of response analysis of buried pipes crossing fault accounting for equations of equilibrium and compatibility of displacements to derive the axial force applied on the pipeline. Recently, Trifonov et al (2010) anticipated a semi-analytical approach for the response analysis of buried pipe crossing the active faults introducing the contribution of transverse displacement to the axial elongation and also allowing different types of fault kinematics.

The above described researches focus on the deformation of pipes and consider the simple spring system for the soil pipe interaction. So far almost all the research work has been done using Finite element method to analyze the response of pipes owing to fault movement. However, discrete element method (DEM) is a powerful tool for representing the more rational analysis of granular materials and we carry out a numerical analysis of buried pipe using both DEM and FEM. DEM has been used for soil particles and FEM used to calculate the response of pipes. The behavior of force –displacement relation between pipes and particles has been described in this paper.

2. NUMERICAL MODELING

2.1 DEM simulation of soil particles

An important tool in modeling the behavior of granular assemblies is the Discrete Element Method (DEM), developed by Cundall and Strack (1979). DEM simulation can be used to determine all kinds of properties of granular assemblies. The distinct element method is based on a dynamic (time domain) algorithm that solves the equations of motion of the granular assemblies by an explicit finite difference method. A force-displacement relation describing joint behavior at contacts is used to obtain forces that are applied to the blocks at the next time step. Particles are connected to their adjacent particles using normal and shear springs and dashpots.

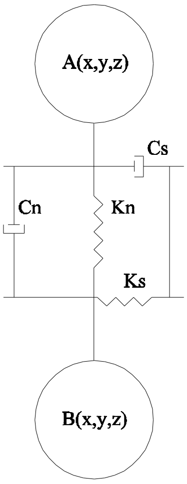

Figure 1. Rheological model of DEM

The Rheological elements of DEM are illustrated in Figure 1. Iwashita and Oda (1998) proposed an additional rotational spring-slider system in parallel with the normal contact spring. This contact model is schematically presented in Figure 2. Normal force is calculated when particle overlap and maximum shear force and moment are given in the following:

$$F_{max} = \mu F_n \quad (1)$$

$$M_{max} = \alpha B F_n \quad (2)$$

Where, F_n is the normal force, μ is frictional coefficient, B is contact area, α is a parameter which determines the rolling resistance.

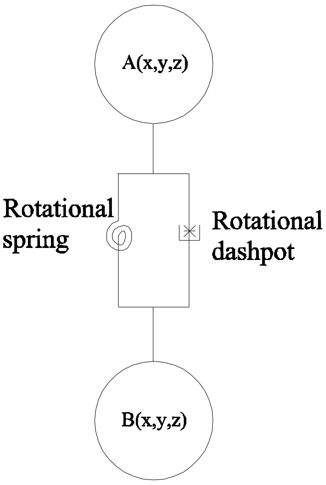

Figure 2. Schematic illustration of rolling resistance

2.2 Pipe response analysis

Pipe is placed in shallow depth in this study. With the increment of DEM computation, particles contact with pipes and force between pipes and particles are calculated using the principle of mechanics. Pipe is considered as 3D beam element and there are six degrees of freedom at each nodal point. Stiffness matrix, mass matrix and damping matrix are formulated considering three dimensional beam elements. Dynamic behavior of pipes has been considered in the analysis and the fundamental equation for pipe is given in Equation (3). Finite Element Method has been used to calculate the responses of pipe elements.

$$F = Ku + C\dot{u} + M\ddot{u} \quad (3)$$

Net contacting forces from particles are distributed on the surface of the pipe elements and these contacting forces are transmitted to the pipe nodal points which set up the deformation of pipes when fault displacement is associated in the model.

3. PROPOSED MODEL

A three dimensional model has been developed to analyze the deformation of buried pipeline under fault movement. Spherical particles are considered as soil particles in the analysis. Around 115 thousand spherical particles are used to put up the model. Use of appropriate diameter of the soil particles is one of the key points in this type of research. Lastly diameter of the particles has been chosen as 1cm after review and considering the computational time. The basement and sidewalls are also made of spherical particles and assumed to be rigid in the analysis. The length and width of the model are considered as 80 cm and 30 cm respectively. The height of the model after the sedimentation process is found to be 29.5 cm. For this analysis the ratio of D_p/D_s is taken as 5, where D_p is the diameter of the pipe and D_s is the diameter of soil particles. Pipe position in the model is set in such a way that it remains fully buried even after the sedimentation process. Typical properties of sandy soil has been considered and the parameters used for pipes and particles are shown Table 1.

Table 1. Parameter of the analysis

Parameters for spherical particles	
Diameter of particles	1 cm
Density of particles	2.5 g/cm^3
Normal spring constant	1.0 x 10^2 N/m
Tangential spring constant	3.0 x 10^1 N/m
Rotational spring constant	3.0 x 10^1 Nm/rad
Normal damping coefficient	0.30 N. s/m
Tangential damping coefficient	0.17 N.s/m
Coefficient of friction	0.5
Parameter for pipes	
Diameter of pipes	5 cm
Modulus of Elasticity of pipes	1.0 x 10^4 N/m^2
No of pipe elements	16

Discrete Element Method (DEM) simulations are exploited for soil particles. Periodic boundary conditions are given at outer edge of the model in strike direction so that if a particle goes beyond the outer edge, it is placed at the opposite edge. This research study includes spherical particles with normal, shear and rolling springs and normal and shear dashpots (Taniyama;2011). Normal force is calculated only when there is an overlap between particles. The effects of tension are not considered in this analysis. Particles move and contact with pipe elements during the strike slip and the resulting contact forces are distributed to the pipe nodal points. Pipe is divided into sixteen equal length elements and pipe responses at each nodal point are calculated considering the dynamic behavior of pipes i.e. stiffness matrix, mass matrix and damping matrix are formulated and used in the calculation.

Seismic fault plane is considered perpendicular to the pipeline axis at the pipeline middle section and divides the whole model in two equal parts. Fixed boundary conditions are applied at the far end of the pipeline. Displacements along the strike direction are constrained at the two extreme nodes of the pipes whereas other degree of freedoms at those points is completely fixed.

The analyses are conducted in two steps: first DEM simulation is performed and subsequently fault movement is imposed to the model. For giving fault motion, the basement is divided into two halves. The divided basement and sidewall move in opposite direction at 5 cm/sec for generating strike slip fault movement. The slip rate 5 cm/sec is preferred in this research is stand on the convergence of the analysis and review of previous numerical research in this field (Kuwata et al; 2003).The complete analysis is being performed using numerical code written in C language. The layout of the proposed model is outlined in the Figure 3.

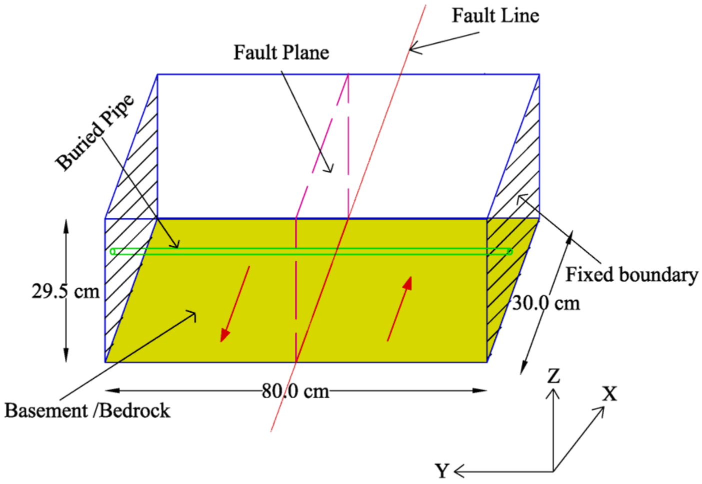

Figure 3. Layout of proposed model

4. RESULTS

Deformation response of pipeline with the increment of fault movement has been observed in the Figure 4. Pipe deforms with the increment of fault slip and attuned with the analysis. Boundary condition is given at the two ends as the same magnitude of fault movement for compatibility of the analysis. From the analysis, it is seen that near the fault crossing point, the deformation of pipes due to particle movement is much higher. This statement is contented by showing the Figure 5. In Figure 5, horizontal axes represent the length of the pipe and vertical axes stand for the force between pipes and particles. With the increment of fault slip, the contributing force for pipes increases i.e. particle moves and they pushes the pipes and resulting much deformation of the pipes. The magnitude of forces between pipes and particles in opposite side of the fault line has almost the same value.

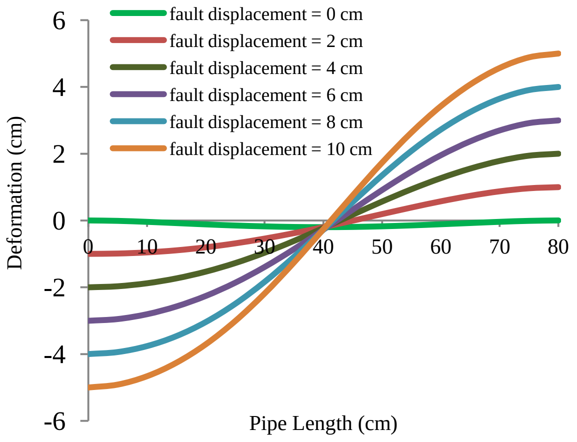

Figure 4. Deformation response of pipe

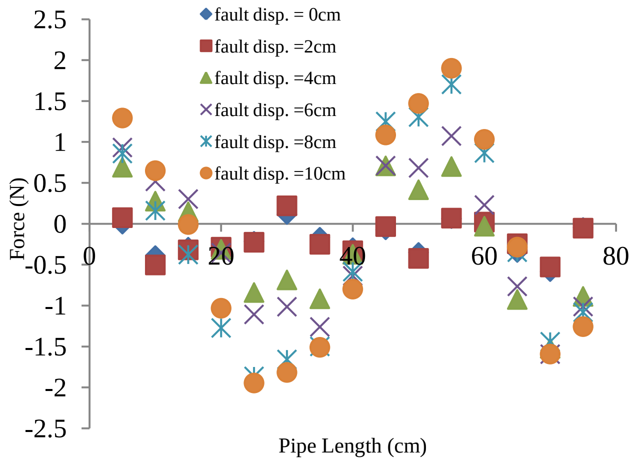

Figure 5. Force between pipe and particles

Maximum force between pipes and particles along the length of the pipeline is shown in Figure 6. Pipe length is represented along the horizontal axes whereas vertical axes show the maximum force response due to the fault movement. Near the fault crossing point, the maximum force between pipe and particles are higher and has opposite magnitude on either side of the fault line which signifies the effects of particles on the pipe. Particles near the fault crossing point exhibit higher forces.

Axial strain in the pipe element has been contributed by particle movement and increased with the increment of fault displacement. The response of maximum axial tensile strain and compressive strain with fault slip are shown in Figure 7. Incremental fault displacement has been plotted along horizontal axes, whereas corresponding strain (compressive and tensile) are plotted in the vertical axes. The above mentioned figure shows that tensile strain increment is faster than compressive strain. In the current model, tensile strain is almost 22% higher than compressive strain. With the increment of fault slip, pipe undergoes more deformation results the strain increment which is illustrated in Figure 7.

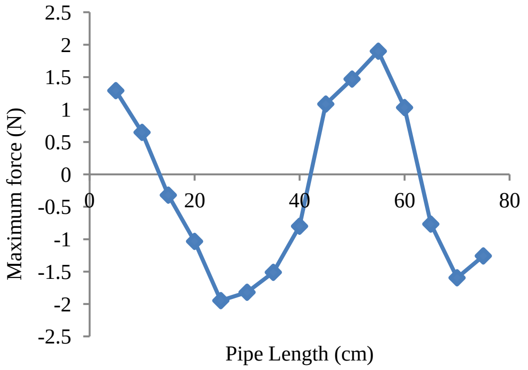

Figure 6. Maximum Force between pipe and particles

One of the key points in this research study is to describe the relationship between soil particles and pipes. The conventional force-displacement correlation of soil springs in axial horizontal and vertical direction follows the linear relationship. In this study, only the axial force-displacement relationship has been discussed. The relative displacement of particles is not considered in the force-displacement behavior. The force between pipes and particles and deformation of pipes are used to depict the load-deformation behavior of pipes. Force deformation curve at each nodal points of the pipe element has been outlined to explain the soil-pipe interaction. Force deformation curve of the nodal points which located near the fault line are shown in Figure 8.

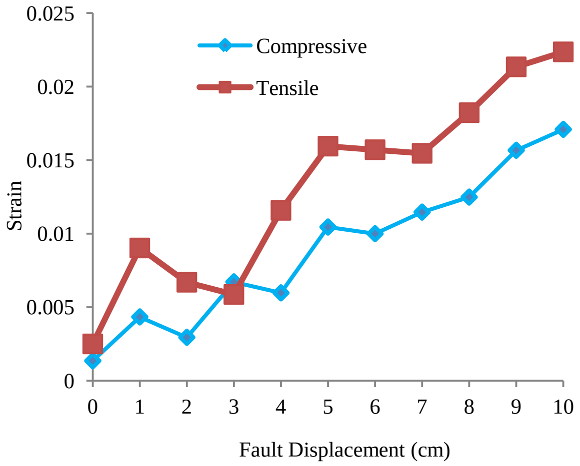

Figure 7. Pipe axial strain

The result shows the effect of particle behavior on the pipe element. Initially the effect of particle force on the deformation of pipes is small; gradually increases and after some initial displacements the pipe load deformation curve shows trend of typical load deformation relation. The relation between the fault displacement and the maximum force has also been outlined and correspond to Figure 9. The above mentioned figure shows the liner relationship between fault displacement and the maximum force between pipes and particles.

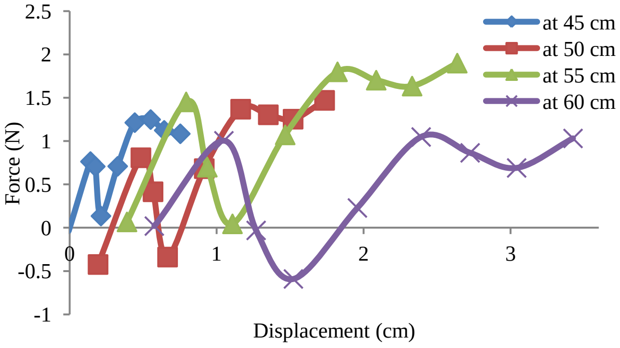

Figure 8. Force –deformation relationship

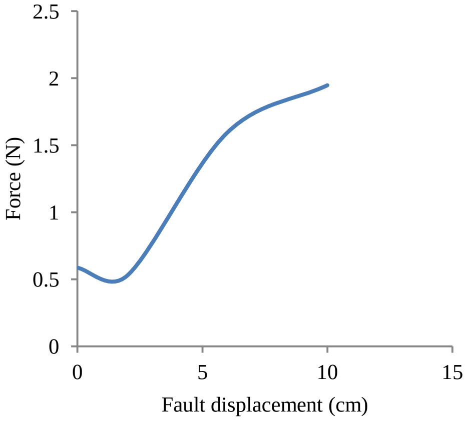

Figure 9. Fault displacement and force relation

5. CONCLUSION

A three dimensional hybrid simulation of Distinct Element Method and Finite Element Method has been done for the response analysis of pipes buried in shallow depth. Instead of using simple spring system to represent the soil pipe interaction, a more realistic situation has created in this research study. Spherical soil particles cover the pipes and strike slip fault movement has been given to the model. Pipe deforms with the movement of particles at the time of fault rupture and exhibits strain increment accordingly with the fault slip. Particle effects on the pipe have been observed more momentous near the fault crossing point. Force –displacement behavior is one of the important factors in buried pipe analysis. We also discussed about the behavior of load –deformation curve for this model. The relationship between forces and deformation are understandable and compatible with the analysis. In this research pipe length was taken as 80cm and particle diameter as 1cm due to the limitation of computational time but more detailed analysis can be done in future with the increment of pipe length and also for different types of fault rupture propagation.

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