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On The Effect of Burial Depth Increase on dynamic Response of Pipelines, Embedded In Soil Slope by Numerical Modeling

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Abstract

Not only do Pipelines, as routes to convey energy (gas and oil), have significant role in countries economy, but also tie intercontinental relations by economic collaborations. Therefore, governments annually allot budgets to ensure their safety and permanent operation against unpredicted events. Consequently, many researches have been performed on the task and many methods have been suggested to guarantee their function and to prevent their failure during PGDs. However, not limited to, but PGDs are principally caused by dynamic loading, particularly earthquakes, which have resulted unrestricted damages to pipelines everywhere and unfortunately, these destructions have led to devastative results when the pipes have been buried in potential landslides.

Tehran, Iran's capital, which is constructed on either soil or rock slopes, are in danger of landslides and consequent gas pipe damages during earthquakes. In this regard, Sharif University of technology, have performed several dynamic shaking table tests and many numerical modellings to discover the mechanisms of damage occurrence and to suggest methods to ensure their safety. One suggestion which has been numerically investigated and is reported in this paper is burial depth change.

The numerical modellings have been performed by ABAQUS program and the models have been excited with predicted earthquake. The loading had 3.7 HZ frequency, 25 cycles and 0.32 g amplitude, resembling a 975 year return period record in the area. While the slope included cemented granular materials and had 30^{o} inclination, it had 15 m width, 13 m height and 30 m length. Also, soil nonlinearity along with damping characteristics were introduced to the program by USDFLD subroutines. Adjacent soil horizontal pressure and dynamic behavior were modeled by a function and spring-dashpot systems respectively. Besides, steel gas pipes which followed API-X42 standard had 20" diameter and 0.25" thickness and 0.5 frictional coefficient with soil.

Four burial depths of 1.1 m, as the standard value in Tehran gas pipelines, and three alternatives (2.1, 3.1 and 4.1 m) were modeled and the results were investigated. Numerical calculations which included slope displacement, pipe elastic and plastic strains in horizontal and vertical modes and strains time history, showed the helpful effect of higher burial depths in decreasing pipe deformations. It is showed that increased burial depth has reduced the horizontal and vertical pipe strains up to 76 % for maximum burial depth. Besides, the resultant strains has also been introduced and the useful effect of higher burial depths has been evidenced. Since, the results have been numerically calculated, reliable geotechnical investigations and numerical modellings, before pipeline construction in real cases, are recommended to accurately determine the failure plane depth. As, placing the pipe beneath the predicted depth, where possible, has proved advantageous in decreasing pipe deformation.

Keywords: Earthquake induced Landslide, Gas Pipeline, Burial depth, Numerical Modeling,

1. Introduction

Lifelines, categorized as energy, water treatment, transportation and information systems are seriously affected by dynamic displacements. Pipelines, the important elements of lifelines, are undoubtedly vulnerable to PGDs and the annual economic loss reports of countries confirm this judgment. Thus, any unprecedented event, endangering these structures, not only can decelerate economic development, but also can create life difficulties in specific areas. Therefore, many studies have recently been accomplished in the last two decades to reveal the damaging mechanism to pipelines and to anticipate its scale. Also, these studies aimed to propose several scientifically acceptable and practically possible methods to prevent them from functional damage.

Challamel and Buhan [1] introduced a simplified approach to study pipe behavior under static landslide motion. The authors proposed mix modeling method which considered the pipe as a beam element and the soil as a three-dimensional continuous medium. They examined the effects of various parameters (including slope width, slope angle, burial depth, strength ratio, pipe thickness or radius, and condensed pipe geometry) and realized pipe size as a key factor having maximum effect on slope stability factor. However, their inference about insignificant effect of burial depth on slope behavior has been showed in their model and laboratory dynamic tests, and has been confirmed in Sharif University tests [2], the recorded strains and numerical modeling calculations evidenced its importance on pipe response determination.

Ramancharla et al [3] which have investigated vulnerability of buried pipelines crossing faults, have recommended that "the burial depth of pipeline should be minimized within fault zones in order to reduce soil restrain on the pipeline during fault movement".

Consequently, this research, as a complementary study for laboratory tests, aims to numerically investigate the fact by use of ABAQUS F.E. program. While a potential landslide in Tehran area has been selected and 4 possible burial depths have been modeled, the loading parameters have been extracted from seismotectonics report prepared by Sharif University for Tehran Gas Company as the client [4].

2. Modeling Characteristics

Since, the use of finite element to model the landslides under static or dynamic conditions have greatly increased in recent years, ABAQUS v6.12 program has been selected for numerical analysis. However, some divergences between the model and prototype cases seem inevitable, the loading parameters, surrounding soil and pipe characteristics, and boundary condition are selected as close as natural situations. These conditions and modelling parameters are described hereafter. It is noted that numerical modelling algorithm has formerly been verified in Jafarzadeh et al [5, 6, 7, and 8].

Pipelines are influenced by three major factors including ground conditions, seismic scale and intensity, and lifeline features. The research has considered constant situations for seismic scale/intensity and ground conditions, while it has changed pipe features. The PGD source which has been directly related to ground conditions is potential "earthquake induced landslides" in Tehran. While the selected site has been located in western north of the city, the loading parameters and ground features have been extracted from geological/geotechnical and seismotectonics reports allotted to the site (Sharif University [4]). Although, several pipeline features have been assumed constant (including "pipe placement zone", "the geometry of pipelines", "pipe materials", "pipe diameters, joints and forms"), burial depth has been altered in the analyses.

2.1 Loading parameters

The seismotectonics report had reviewed the potential hazards in 150 Km distribution from the base point (Tehran center). A 975 year return period earthquake along with 50 years life time of the structure had been considered in the PSHA analysis. The results showed 0.493 g peak amplitude acceleration with 3.7 Hz frequency record. However, the peak acceleration amplitude was, then, converted to a harmonic record of 0.65*0.493 g with regard to Seed method (Kramer, [9]), 3.7 HZ frequency and 25 loading cycles which resembled an 8.5 magnitude earthquake. Fig.1 shows the induced slope base acceleration time history.

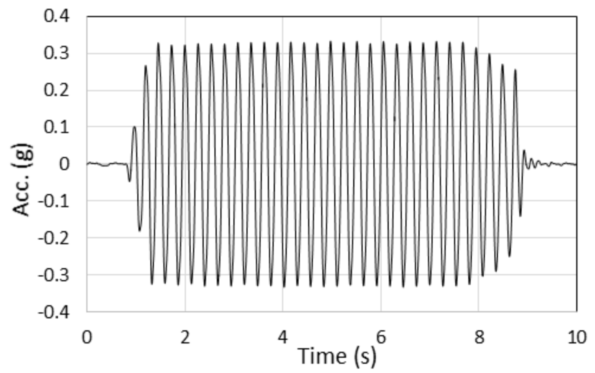

Fig. 1- Dynamic Loading time history at model base

2.2 Soil characteristics

In order to gain reliable results and control mesh sizes in specific regions, the model has been divided to 3 layers. The first part which has had 2 m thick has been uppermost soil layer. The second part which has been located between the 1st and the 3rd part, has similarly had 2 m thickness, whilst had different soil characteristics. Finally, the 3rd model with 8.6 m thickness, possessed the highest elastic modulus and relative density. Table 1 summarizes the layer characteristics in different models. While Mohr-Coulomb behavior model was selected to account for the stress-strain relationship in soils, the nonlinear behavior of the material under dynamic loading has been modelled by USDFLD ABAQUS subroutine written by FORTRAN compiler [10]. The G/G_0 curve follows the instructions proposed by Park et al. [11] and Tika [12], and material damping, attenuating the internal energy generated from seismic loading, has introduced to model by Rayleigh algorithm. Damping coefficients (α and β) have been calculated for dynamic loading frequency (3.7 Hz) and natural frequency of the slope. The natural frequency was calculated through frequency linear perturbation step [10]. While the layers has had damping ratios of 5, 10 and 15%, the detailed information are summarized in Table 1.

Table 1– Soil parameters used for analysis in various layers

Layer No.	**Layer depth (m)**	**C (Pa)**	**Friction angle (deg)**	**E_{max} (MPa)**	**Damping (%)**	**α**	**β**	**γ (Kg/m^3)**	**v_s (m/s)**
1	2	600	30	555	15	1.44	0.0016	1520	375
2	2				10	2.88	0.0033		
3	8.6				5	4.31	0.0049		

2.3 Boundary conditions, model geometry and interactions

Since a typical slope geometry has been selected based on site surveying, Fig.2 shows the slope and pipe in the form of graphical mesh and Table 2 summarizes the models dimensions. Soil and pipe discretization has been performed by 8-node linear brick elements; however the soil elements have "reduced integration point" and "hourglass control" property. According to Lysmer and Kuhlemeyer studies [13], elements dimensions has been selected less than 1/10 shear wave length. The mesh dimensions which have been 80 cm in the bottom, have been changed to 45 cm in near pipe regions and 8 cm for the pipe. However the model has had different base boundary conditions in static and dynamic analysis mode, other surfaces had similar situations. These specifications are summarized in Table 3.

In order to avoid box effect in boundary planes with regard to propagating wave, viscous absorbent boundary elements, using dashpots, proposed by Lysmer & Kuhlemeyer [13] have been used. Additionally, in order to overcome the redundant permanent displacement at low frequencies, normal and tangential springs developed by Kellezi [14] have been applied to unconstrained planes. The soil horizontal pressure has been applied to boundary planes due to Eq. (1). Regarding this formula, which is applicable for all planes and is introduced to the program, the horizontal earth pressure has been linearly increased from zero in uppermost point to the highest one in the lowermost part.

As previously noted, the boundary conditions, being modeled by spring-dashpot system, have been divided to three regions which in turn has followed the corresponding soil layer. Table 4 summarizes the stiffness and damping measures of the system for each region. While the pipe-soil tangential contact can be defined in frictional, frictionless and full contacts algorithms, this study has used penalty frictional contact (Coulomb frictional formulation) with 0.5 friction coefficient (based on laboratory tests). On the contrary, normal behavior has been defined by hard contact, allowing separation of surfaces, while preventing the salve surface (soil) to penetrate the master one (steel pipe).

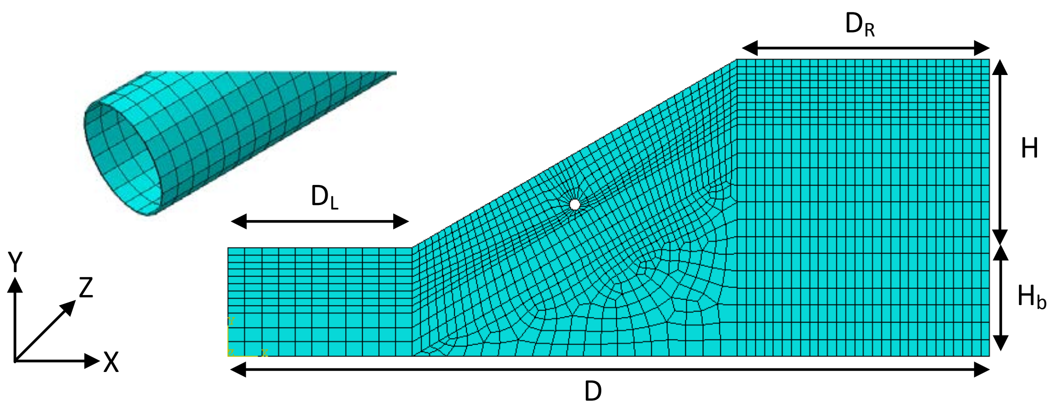

Fig. 2 – Typical slope dimension for the dynamic analysis

Table 2 – Soil parameters used for analysis in various layers

Model No.	**H (m)**	**H_b (m)**	**D_L (m)**	**D_R (m)**	**D (m)**	**W (m)**
1	8.7	4	6	9	30	15
2		5				
3		6				
4		7				

Table 3 – Boundary condition for slope planes in dynamic condition

<table>
<tr><th>Plane name</th><th>Ux</th><th>Uy</th><th>Uz</th></tr>
<tr><td>X=0, X=D</td><td rowspan="3">Not constrained</td><td rowspan="2">Not constrained</td><td rowspan="2">Controlled by horizontal earth pressure and spring dashpot system</td></tr>
<tr><td>Z=0, Z=w</td></tr>
<tr><td>Y=0</td><td colspan="2">constrained</td></tr>
</table>

$$\left[\frac{\frac{H}{(D-D_R-D_L)}(x-D_L)-(y-H_b)}{\frac{H}{(D-D_R-D_L)}\times(x-D_L)+H_b}\right]\times\left[\frac{1-\frac{H_b}{(H+H_b)}}{(D-D_R-D_L)}(x-D_L)+1\right]\times A \qquad (1)$$

where A represents the maximum horizontal earth pressure at model base and x, y, H, D, D_L, D_R and H_b are introduced in Fig 1.

Table 4 – Spring stiffness and dashpot coefficient in different layers []

Layer No.	Normal direction		Tangential direction	
	Spring stiffness* (N/m)	Damping coefficient* (N.s/m)	Spring stiffness (N/m)	Damping coefficient (N.s/m)
1	$8.6*10^7$	$1.1*10^5$	$5.0*10^7$	$4.3*10^4$
2	$2.0*10^8$	$1.7*10^5$	$1.1*10^8$	$6.4*10^4$
3	$6.1*10^8$	$5.1*10^5$	$5.0*10^8$	$3.8*10^5$

*: for detailed information refer to Jafarzadeh et al [8]

2.4 Pipe characteristics and burial depths

However both polyethylene and steel pipes are used in Tehran gas Network; due to more usage; the steel pipe has been selected for the analysis. The pipe grade which followed API-5L-X42 steel, has had 200 GPa elastic modulus and 0.3 poison ratio, also, it has had 20" outer diameter and 0.25" thickness and has been buried in mid-length of the slope (Fig.2).

The modes of pipeline deformations are greatly dependent on loading direction, as a case in point, the ground deformation can be parallel or normal to pipe axis. Bruschi et al [15] modelled the slow soil movement for intersection angle of 10, 40 and 70 degrees and concluded that "the induced axial force of pipe increases with decreasing pipe-slope angle", and "the bending moment has direct relationship with that angle". Permanent Ground Deformation perpendicular to pipe axis, similar to this study, can be considered spatially distributed or localized abrupt. Although, in first case, the pipe strain is a function of both the amount and width of the PGD zone, it is dependent on PGD in latter case, (M.J. O'Rourke & X. Liu [16]). While this paper considers the 90 degree intersection angle to account for pipe deformations, the spatially distributed pattern is verified for pipes embedded in slopes (Fig.3).

The numerical models have been divided to 4 categories. While the pipe has been buried in mid-slope section, it has had 4 various burial depths due to practical experiences. Although the standard burial depth has been 1.1 m from pipe crest, in particular situations, 4 m burial depth has been also executed. Thus, the numerical analysis has considered 2.1, 3.1 and 4.1 m burial depth to reveal its effect on pipe deformations.

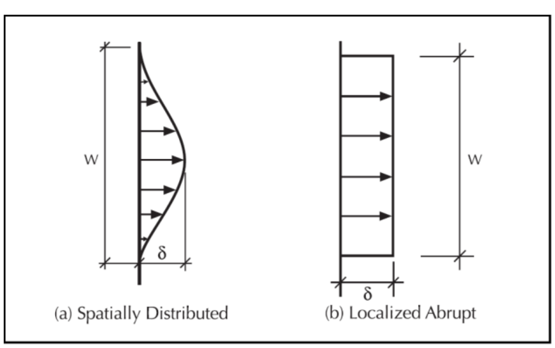

Fig. 3- Two ground deformation type perpendicular to pipe axis (after M.J.O'Rourke & X.Liu [16])

3. Numerical analysis results

The numerical models have been constructed and analyzed by ABAQUS program. The burial depth which was 1.1 m in model one, has been increased to 2.1, 3.1 and 4.1 in 2nd, 3rd and 4th model respectively. In the first stage of the analysis, the models have been statically analyzed to reach the equilibrium state, then dynamic loading has been applied to model base ("Y=0" plane) and the results have been calculated. While Fig.4 has graphically displayed the horizontal displacement and soil subsidence in four models, Table 5 has compared model displacements after dynamic excitations.

However model dimensions, material characteristics and dynamic loading parameters, were similar, the horizontal displacements and soil subsidence differed. This phenomenon, referring to pipe placement geometry, shows burial depth effect on slope deformations. In other word, higher burial depths, has decreased model horizontal displacements. This value, which was 67 cm in model 1, has decreased to 61, 55 and 51 cm in the 2nd, 3rd and 4th model respectively. The graphical diagrams of slope movement (Fig.4) evidence the appropriate slope dimensions, since the horizontal slope displacement and failure plane have been limited to steep section of the slope and have not been extended to model boundaries, consequently; the numerical modelling algorithm has the capacity to calculate the entire displacements and deformations during and after dynamic loading. It is noted that the model dimensions have been selected due to Jafarzadeh et al studies [5].

Since, having been calculated in slope crest and being far enough from pipe placement zone, the maximum soil subsidence has not been influenced by burial depths. In contrast to horizontal displacements, Fig.4 and Table 5, display no noticeable change in maximum vertical displacement in different models.

Since reflecting slope displacements effect on buried structure, the pipe strains are of great importance. Consequently, they are calculated and displayed in this paper. The strains, parallel to pipe axis, have been divided to horizontal and vertical ones, which in turn refer to either horizontal pressure or soil overburden changes as a result of dynamic loadings. As a case in point, Table 6 summarizes the maximum calculated values in models. In addition to these strain types, the resultant strain which captures the effect of horizontal and vertical strains and has the potential to form the basis of judgments, is calculated and displayed in Table 6.

While the $4.3*10^{-3}$ horizontal strain in model 1, has decreased to $2.9*10^{-3}$ in model 2, $1.4*10^{-3}$ in model 3 and $1.1*10^{-3}$ in model 4, the vertical strains show similar behavior. Since $2.4*10^{-3}$ vertical strains of model 1 has decreased to $1.1*10^{-3}$, $5.6*10^{-4}$ and $3.1*10^{-4}$ in 2nd, 3rd and 4th models respectively. In the same way, the resultant strain values confirm the decreasing trend of pipe deformations in higher burial depths. As a case in point, $4.9*10^{-3}$ strain in model 1, has decreased to $3.1*10^{-3}$, $1.5*10^{-3}$ and $1.1*10^{-3}$ in the 2nd, 3rd and 4th model respectively. The strain values show 37, 69 and 76 % decrease in comparison to standard one (1.1 m) (Table 6).

Although the pipe strains are divided to horizontal and vertical deformation modes, they are divided to elastic and plastic types. Knowing the fact that elastic strain limit is equal in all models ($2*10^{-3}$), the plastic strains are only displayed in Fig.5. This value which were 3×10^{-3} in model 1, has been decreased to 1.6×10^{-3} in model 2, 1.4×10^{-4} in model 3 and zero in model 4. The decreasing trend of pipe strains in higher burial depths shows the beneficial effect of burial depth increase in models.

Table 5 – Models displacement after dynamic loading

Model No.	Maximum Horizontal Displacement (cm)	Maximum Soil Subsidence (cm)
1	67	27
2	61	38
3	55	36
4	51	34

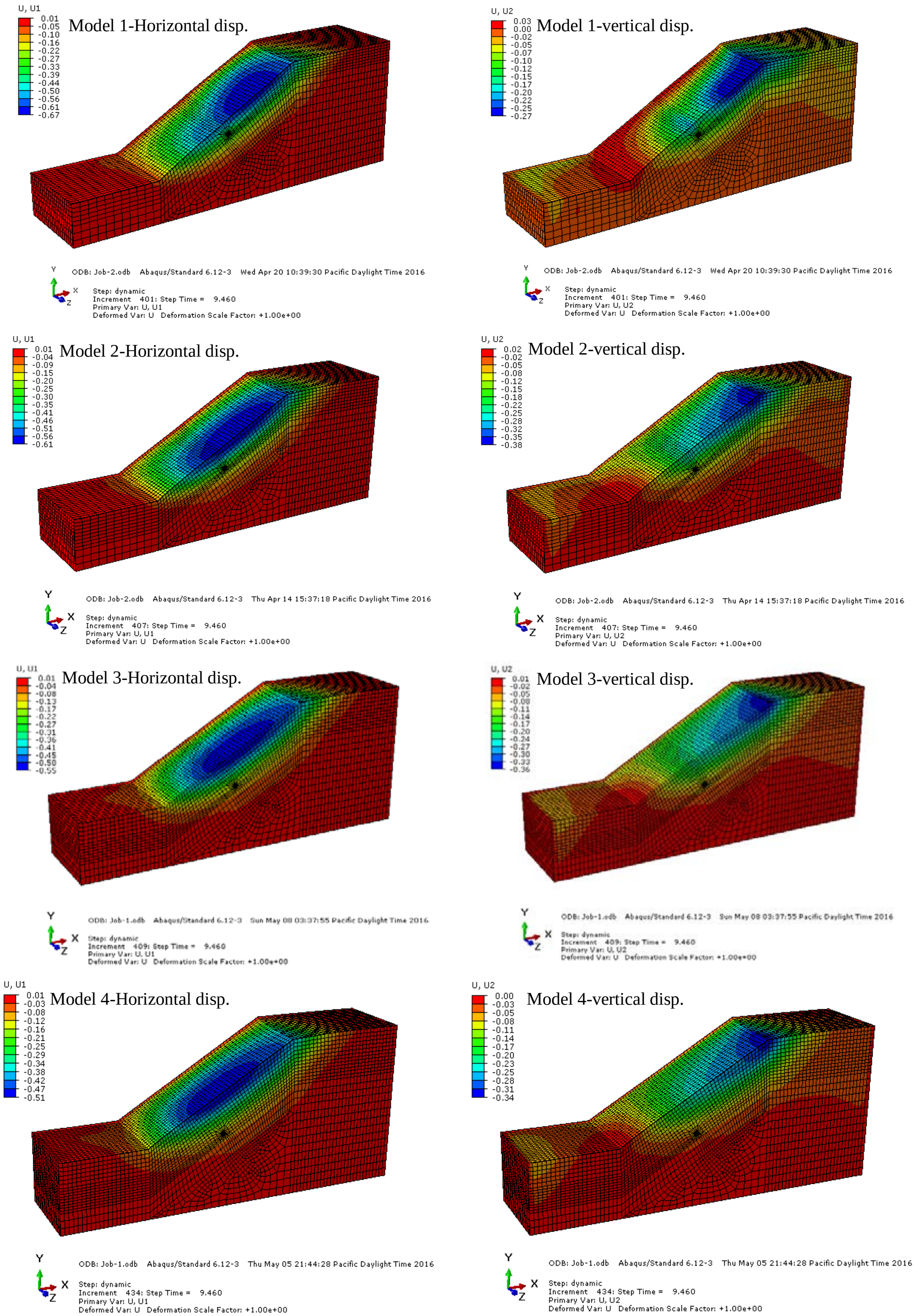

Fig. 4 - The horizontal and vertical displacement after dynamic loading in various models

Table 6 – Mid-section pipe strains after dynamic loading

Model No.	Horizontal Strains ($*10^{-3}$)	Vertical Strains ($*10^{-3}$)	Resultant Strains ($*10^{-3}$)	Strain Decrease (%)
1	4.3	2.4	4.9	-
2	2.9	1.1	3.1	37
3	1.4	0.56	1.5	69
4	1.1	0.31	1.1	76

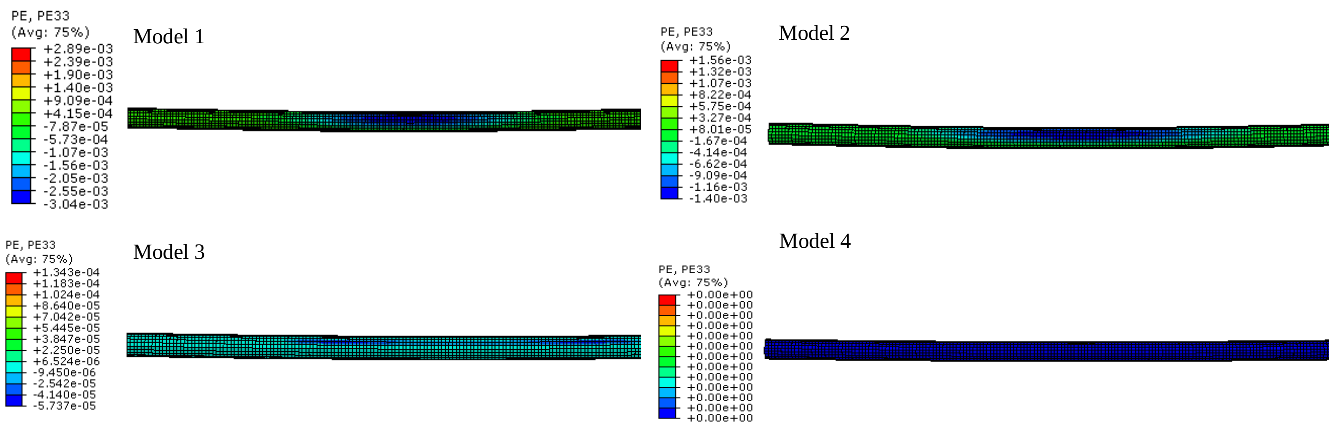

Fig. 5- Plastic strains in buried pipes

Since burial depth changes are expected to considerably influence the vertical strains rather than horizontal ones, Fig.6 displays the strain time history during excitations. Although strain graphs reflect the sinusoidal nature of excitations, they show the increasing trend of residual strains from onset of loading to its completion. This trend shows the plastic strain accumulation in each loading step while the elastic one keeps its nature of reversibility. As a case in point, the final vertical plastic strain in model one has increased from zero in t=0 s to $2.4*10^{-3}$ in t=9.5 s. While, the buried pipe has $\pm 2*10^{-3}$ elastic strain limit, this value should be added to plastic ones, to form the maximum pipe deformation due to dynamic loading. The final plastic strain for the 2nd, 3rd and 4th pipe has been $1.1*10^{-3}$, $0.6*10^{-3}$ and $0.3*10^{-3}$ respectively. Although the pipes' vertical response reflect the cyclic nature of resembled earthquake loadings, it experienced extra number of cycles than the model base (N>25 cycles). In other words, the pipes excitation frequency have been higher than loading, which in turn reveals near pipe slope dynamic displacements frequency.

Additionally, the strain graphs show negative vertical strains in higher burial depths (Fig.6). In contrast to standard burial depth (1.1 m) which shows increasing trend of vertical strain from t=0 to T=9.5 s, other models with higher burial depths, have shown negative vertical strains in opposite direction, particularly in T=1.5 to T=2 s for model 2, T=1.5 to T=2.5 s for model 3 and T=1.5 to T=4 s for model 4. This phenomenon reveals that "in increased burial depths the buried pipes experience cyclic upward movement in the first seconds of dynamic loading and the period for which this event occur elongate in higher burial depths".

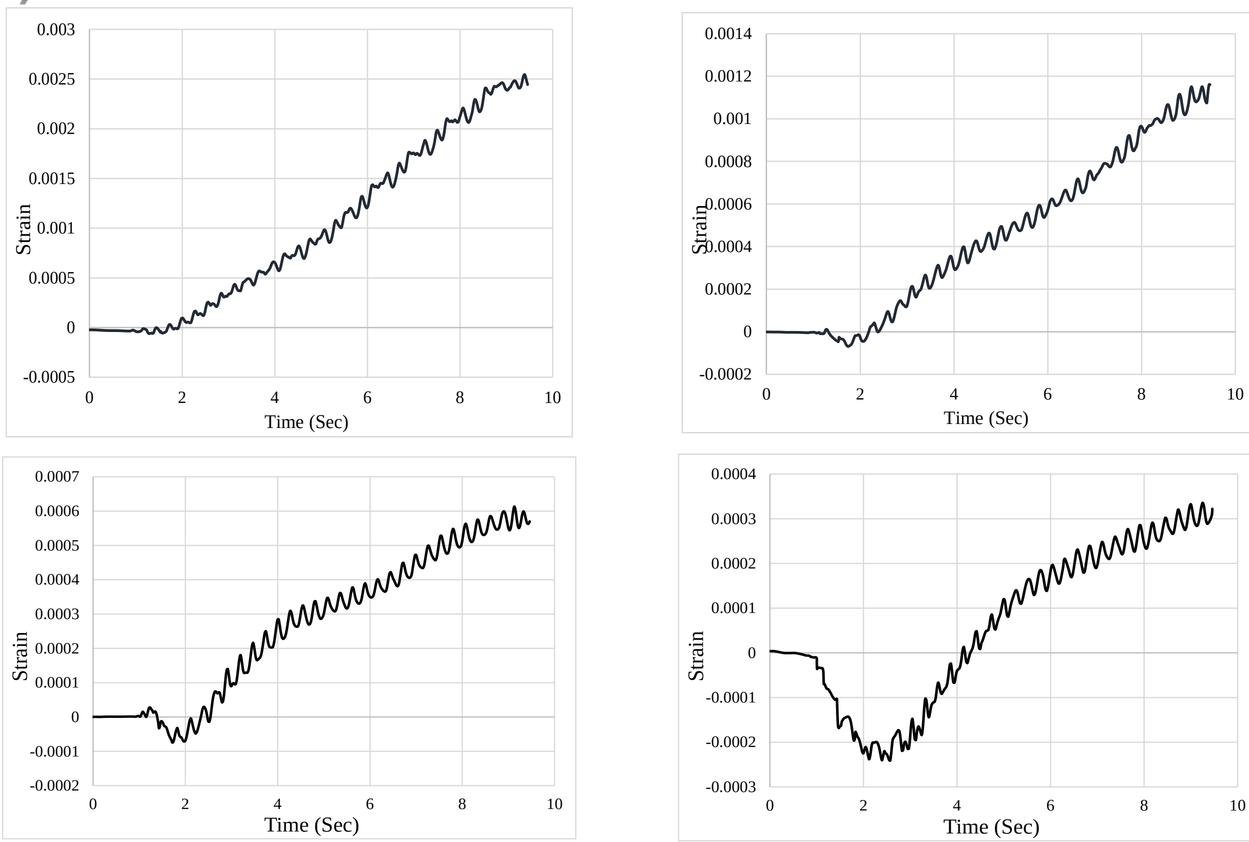

Fig. 6 - Total vertical pipe strain in model 1 after dynamic loading in mid-length of the pipe

4. Discussions

4 numerical analyses has been performed and the useful effect of burial depth increase in lowering embedded pipe deformations in sandy slope has been shown. Since the strains has been divided to vertical and horizontal ones, the comparisons should be based on this division. Regarding to Fig.5 and Table 6, increasing pipe burial depth has greatly influenced pipe deformations. The horizontal strains which in turn directly capture the effect of horizontal slope displacements has decreased in higher burial depths. Since the slope horizontal displacement reaches the peak value in shallow depths and attenuates in higher measures, it seems logical that "higher burial depths leads to lower pipe horizontal strains". This phenomenon is evidenced in Fig.7, displaying the horizontal pipe strains distribution in various models. Provided that "x" shows the pipe section with regard to its length, 0<x<3 and 12<X<15 displayed the regions for which the pipe horizontal strains have not changed in various burial depths. However if the <3<X<12 confirms, higher burial depths have resulted lower pipe horizontal strains. This difference reaches it maximum in pipe mid-length.

In contrast to horizontal strains, the vertical ones are the result of pipe overburden changes and need more considerations. Because, the pipe overburden height has different behavior along slope length, particularly in sandy slops. For instance, any slope, having experienced subsidence in crest and upper part, resulting in less burial depths than pre loading state, will undoubtedly encounter higher soil height in lower and toe parts. Since, the sliding material have displaced from crest section and upper parts to lower regions, which either has decreased or increased pipe overburden respectively. Thus, analyzing vertical slope movement and consequent vertical pipe strains needs more caution, as it depends on pipe trench geometry with regard to slope length. Thus, analyzing burial depth effect on pipe strains needs additional parameter to reflect soil displacements. Consequently, a parameter is introduced, "S", and defined as Eq. (2):

$$S = \frac{D_O}{D_H} \times 100 \quad (2)$$

where D_o represents the predicted pipe overburden in the vicinity of pipe trench and D_H shows the maximum horizontal soil displacement in a slope. Finally, S expresses their percentage ratio in a dimensionless form. Although soil subsidence from crest or upper slope part decreases pipe burial depth, soil horizontal displacements toward lower parts increase pipe overburden in lower slope parts or toe section. Thus, the vertical soil movement leading to overburden increase is assumed in plus direction, while upper slope sections with decreased burial depths is assumed minus one. Consequently, "S>0" shows increased burial depth with reference to pre-test condition and "S<0" represents the region for which the pipes lose their overburden pressure. As a case in point, while Fig.8 shows vertical models displacements in mid-section of the slope where the pipes has been buried, it summarizes the "S" values for numerical models.

Regarding to S values for different models, the pipes buried in midsection part, has experienced lower burial depth after dynamic excitations. Such as, the numerical modellings show S= -19 to -14% in models. Consequently, if the S value, reaches higher quantities (S4>S1), the effect of burial depths in decreasing pipe strains are highlighted (Fig.8). However, this inference should be evaluated by physical modellings and its correctness needs verification. This situation will be emphasized when the slope experiences higher soil subsidence in upper part including crest section. Since, buried pipes recline on the elastic granular materials (sand) and higher vertical deformations will remove the support, it will cause the pipes to experience higher vertical strains (S<0). On the contrary, dynamic loading causes the sliding material to move toward the lower part which will increase pipe burial depths (S>0). Although, increasing burial depth will result higher vertical static pressure on the pipe, the phenomenon should be dynamically analyzed to discover its effect on pipe vertical deformation. This paper which consider the pipe in the mid-section of the slope, only examines one probable case, however, it is more possible that the pipe passes other slope sections like the crest, toe or other parts.

Regarding to Fig.7, which displayed the vertical strain distribution in various models, the 4th model with S=-14 has had the lowest maximum vertical deformation than other pipes ($6*10^{-4}$). The 3rd, 2nd and the 1st models which have had S=-16, -18 and -19 respectively, have experienced higher vertical strains ($7.5*10^{-4}$, $1.1*10^{-3}$ and $2.2*10^{-3}$). Similar to horizontal strains, the first and the last pipe sections which have had 0<x<3m and 12m<x<15m, have experienced almost equal values, while different situations have occurred for other segments. Additionally, the maximum pipe deformation section which has been located in pipe mid-length for 1.1 and 2.1 burial depths, has displaced to 1/5 length of the pipe (which is near to zero deformation zone) for 3.1 and 4.1 burial depths. This phenomenon shows that "there has been a threshold burial depth, over which increasing this value has no effect on pipe strains". Since, the mid-length strains have become lower than near end deformations. Such as this study, for which increasing pipe burial depth from 2.1 m to 3.1 m, has caused the maximum section strain relocation from pipe mid-length to near support region, while the $5.6*10^{-4}$ mid-section strain has increased to $7.5*10^{-4}$ in pipe ends (model 3). Thus, it is considered that the optimized burial depth for current situation has been a value between 2.1 m and 3.1 m, although it needs sensitivity analysis.

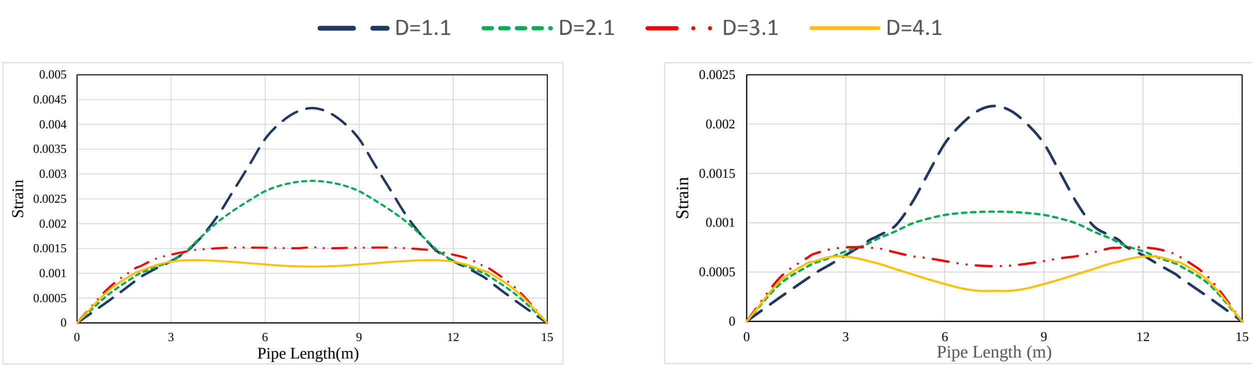

Fig. 7 - Pipe strain distribution along its length in different burial depths

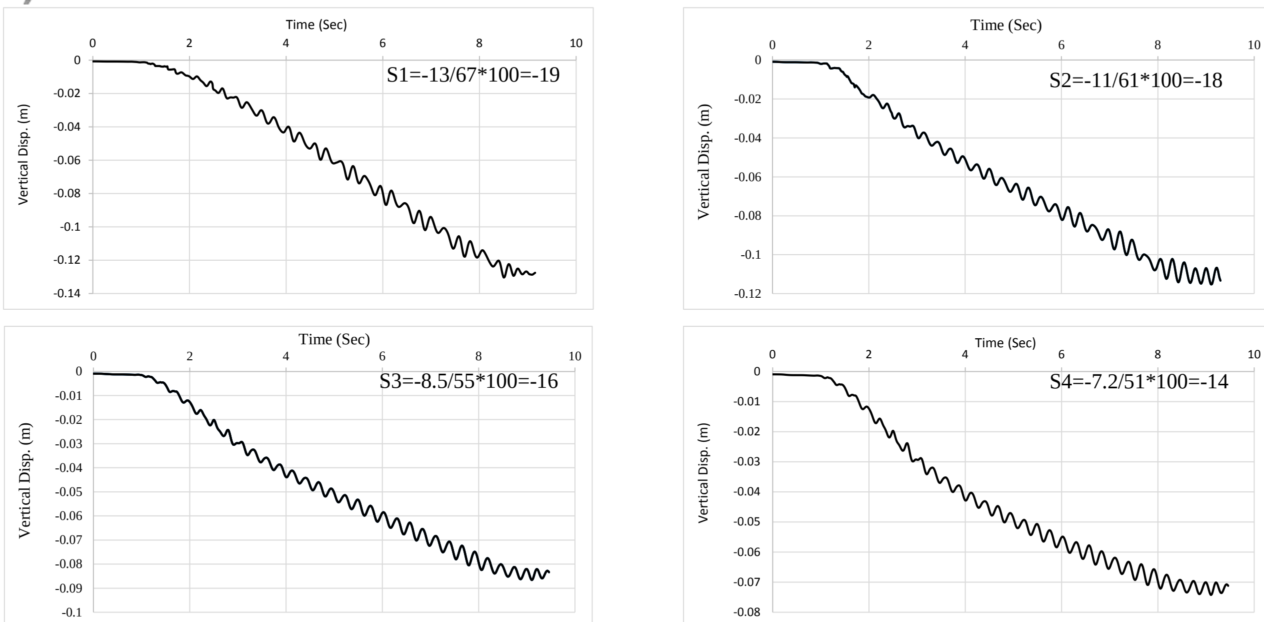

Fig. 8 - Vertical soil displacement time history in models
for mid-length of the pipe and "S" values for different models

5. Conclusions

Since, pipelines are in danger of either structural or functional damage under PGDs conditions, and Landslides as an important element of PGDs, have frequently occurred worldwide, many studies and research programs have recently been performed to discover the interaction mechanisms and to propose practical methods, in order to reduce their vulnerability and to make their damages controllable. This study, as a part of a thorough scientific research project, focusing on pipeline-landslide interactions, numerically evaluates burial depth changes effect on dynamic response of buried pipes in unstable soil slopes.

Regarding to mentioned data, 4 numerical models were constructed and analyzed by ABAQUS program. While the models have had similar dimensions, material characteristics and loading parameters, the pipes burial depth has been changed. The burial depths have been selected due to Iranian gas pipeline standards (1.1 m) and practical experiences in Tehran city (up to 4.1 m). The models were dynamically excited by a resembled 975 return period earthquake which had 0.32 g amplitude, 3.7 HZ frequency and 25 cycles. The pipe strains have been divided to 2 major categories as (a) strain direction which in turn has been separated to horizontal and vertical parts, and (b) elastic or plastic ones. Also, the horizontal and vertical pipe strains have been combined to form the resultant pipe deformations.

The results show the useful effect of burial depth increase in lowering pipe deformations. Numerical calculations have shown that increasing burial depth from 1.1 to 2.1 m, has decreased the pipe resultant strains up to 37%. This value has been increased to 69% for 3.1 and 76% for 4.1 burial depths. Consequently, burial depth increase has proved its useful effect on decreasing pipe strains. It is noted that, this result should be verified with laboratory dynamic tests which can be performed by shaking table or centrifuge device.

Additionally, since pipe vertical strains are the result of burial depth changes along slope length, they are greatly influenced by soil vertical displacement. Consequently, a dimensionless parameter, "S", which reflects the slope vertical displacement along its length has also been introduced and a brief description of numerical models results, with reference to this parameter, has been presented. While the results have shown that "higher "S" values has led to lower pipe strains" sensitivity analysis and further studies are also recommended to reach more accuracy.

Furthermore, the numerical results have shown that "there is a threshold burial depth over which increasing this value will have no concrete influence on pipe strains". Even though, this value, for this study, has been evaluated between 2.1 and 3.1 m, its significance necessitates a planned research activity to reveal the value in a dimensionless form. Also, the strain distribution diagrams along pipe length, presented for each model, have evidenced that, higher burial depths than the threshold one, have rearranged the maximum strain section from mid-length of the pipe to near end segments.

In summary, although helpful, burial depth increase plan needs geotechnical investigations and verified numerical modellings, before pipeline construction, in order to accurately predict horizontal and vertical slope displacement, and, to determine the failure plane depth with reference to slope length, since, placing the pipe beneath the predicted depth, where possible, has proved advantageous in decreasing pipe deformation.

6. Acknowledgement

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7. References

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