

Damage Assessment of Buildings Due to Different Parameters of Pipeline Deterioration

Metwally k. G.¹, Hussein M. M.² and Akl . A. Y.²

Structural Engineering Department, Faculty of Engineering, Benisuef University¹, Structural Engineering Department, Faculty of Engineering, Cairo University², Egypt
manar.m.hussein@gmail.com

Abstract: Due the high interaction between sewer pipelines deterioration and existing structures in urban areas, the operation of pipeline failure in urban areas draws much attention. In this study a thorough analysis of the pipeline failure influence in different soils on adjacent buildings was investigated. Numerical simulations were performed by means of the finite element program ANSYS/CivilFEM. The purpose of the coupled analyses (soil, pipeline and building in the same model) was to investigate the general mechanisms of soil structure interaction that occur in this type of problem. Each of these analyses produced a large amount of output data. This study highlights how the ground surface and building foundation displacements are used to estimate the damage category of buildings due to failure in pipeline. The variable parameters used to simulate the pipeline failure are pipeline settlement, position of settlement, burial depth, soil stiffness, infiltration of sewage and groundwater. For each case, results are presented as vertical and horizontal displacements of ground beneath building and estimated category of damage is calculated.

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1. Introduction

This paper investigates the interaction between the pipeline failure and adjacent structure. It also develops the coupling effect models of pipeline failure, soil, foundations and upper structure. A full three-dimensional finite element analysis, "ANSYS+CivilFEM", which takes into consideration the elasto-plastic behavior of the soil, the pipeline failure mechanisms and the presence of the structure, is employed to perform the study (Swanson 2007). The results of the models include the vertical settlement and horizontal displacement of the foundation of the adjacent structure.

Analysis of the pipeline-structure interaction problem is performed in two steps (steady state and pipeline failure state). The pipeline failure operation is modeled by either the settlement of pipes or reducing the stiffness of soil around the pipeline.

Settlement of structures, whether from nearby pipeline failure or other causes, can result in noticeable damage. Such damage can be significant and costly. Usually, the most settlement sensitive buildings are those with frames with masonry in-fill walls or masonry load bearing walls. Simplified criteria including "angular distortion", "deflection ratio" and "horizontal strain" have been used to assess such damage. By combining ground deformation patterns, well-known damage category criteria, strain superposition and critical strain concepts, the potential effects of building deformations can be estimated with a great accuracy. The report by Aye (2007) was used as a basic reference in ground

deformation prediction and building damage assessment. For cut-and-cover excavation zone, the work of Ruwanpura (2007), Clough (1990) was used whereas published papers of Burland (1977), Boscardin and Cording (1989) were applied for bored tunnels. The damage categories are based directly on the descriptions of damage provided in Table 1.

The cumulative tensile and principal crack widths were calculated from the output settlement and run within spreadsheets. The simple cumulative deformation was used directly considering that the buildings may have exhibited some initial cracking due to construction defects, thermal cracking, or from ageing. In addition, calculation of tensile cracks were calculated at the first bay of building (from 5.0 to 10.0 m), because it is the nearest place to pipe failure.

The numerical model result was used to estimate the effect of each of the main parameters that induce pipeline failure on the category of damage of adjacent buildings. These parameters include the pipeline settlement, position of settlement, burial depth, soil stiffness, infiltration of sewage and groundwater. The numerical modeling was previously adopted to analyze such problem for a practical case study by Metwally (2009) and fairly accurate results were achieved (A&A 2008).

2. Numerical Modeling

Figure 1 depicts the problem under consideration which is used to quantify the interaction between sewer pipeline and the reinforced concrete building. The pipeline is characterized by its

depth H , diameter D , pipe thickness e , while the building is modeled by a spatial reinforced concrete

framed structure with floor height 3.0 m and column's spacing 5.0 m in two directions.

Table 1: Building damage classification after Burland (1977) and Boscarding and Cording (1989)

Risk Category	Degree of Damage	Description of Typical Damage	Approximate Crack Width (mm)
0	Negligible	Hairline cracks	Null
1	Very Slight	Fine cracks easily treated during normal decoration	0.1 to 1
2	Slight	Cracks easily filled. Several slight fractures inside building. Exterior cracks visible	1 to 5
3	Moderate	Cracks may require cutting out and patching. Door and windows sticking	5 to 15 or a number of cracks > 3
4	Severe	Extensive repair involving removal and replacement of walls, especially over doors and windows. Windows and door frames distorted. Floor slopes noticeably.	15 to 25 but also depends on number of cracks
5	Very Severe	Major repair required involving partial or complete reconstruction. Danger of instability.	> 25 but depends on number of cracks

The behavior of the building is assumed to be linear-elastic. The soil behavior is assumed to be governed by an elastic perfectly-plastic constitutive relation based on the Mohr–Coulomb criterion with a non-associative flow rule.

Numerical simulations were performed by means of the finite element program ANSYS/CivilFEM. Analysis of the pipeline–structure interaction problem is performed with two steps (steady state and pipeline failure state). The first step (steady state) is concerned with the determination of initial stresses in the soil mass prior to the pipeline failure. It is performed using a finite element calculation considering the self-weight of both the soil and the structure. Displacements are reset to zero at the end of this stage; consequently, results referred to hereafter are due to the pipeline failure. The second step (pipeline failure state) deals with the numerical simulation for the failure of the pipeline in presence of the structure (Metwally 2004). The pipeline failure operation is modeled by the settlement of pipes or by reducing the stiffness of soil around the pipeline.

2.1. Full Three-Dimensional couple analysis

The full three-dimensional coupled approach is adopted in this research to study the influence of the pipeline failure on the building. The longitudinal

section of the pipeline is assumed to coincide with that of the building. The pipeline and structure characteristics are given by: pipeline diameter $D=2.0$ m, pipe thickness $e=0.2$ m, pipeline depth $H=5.0$ m, the column's spacing in two directions $=5.0$ m, and height of each level $h=3.0$ m. Material properties for soil, lining and structure are listed in Tables 2 and 3.

Finite element analysis for the coupled model is carried out using the mesh presented in Figures 2. The finite element mesh was 30 m long, 12 m high and 30 m wide. Eight-noded brick elements were used to model the soil and the concrete pipe. The structure is modeled using eight-noded brick elements and four-noded shell. In the model, the number of pipes is 15, where the connections between the pipes are contact element. The contact element of pipes connection was taken no separation element. In this element (no separation contact), the two contact surfaces (target and contact surfaces) are tied, although sliding is permitted, elements for the frames and slabs respectively. The pipeline encased in a homogeneous soil mass. The contact element between the foundation of the building and the soil was taken rough element. In this element (rough contact), the two contact surfaces (target and contact surfaces) are not slipping, although separation is permitted.

Table 2: Soil and pipeline properties after Metwally (2009)

Soil properties		Pipeline properties	
Soil elastic modulus E_s	2000 t/m ²	Pipe diameter D (interior)	2.00 m
Soil Poisson's ratio ν	0.35	Wall thickness of concrete e	0.20 m
Soil cohesion C	2.00 t/m ²	Pipe length L_p	2.00 m
Angle of internal friction ϕ	30°	Number of pipes in pipeline	20 pipes
Density of soil over pipe γ	1.85 t/m ³	Concrete elastic modulus E_c	3.5E6 t/m ²
Soil height above crown H_t	5.0 m	Concrete Poisson's ratio ν_c	0.20
μ (Between soil& pipes)	0.32	μ (Between pipes segments)	0.60

Table 3: Structural material data after Metwally (2009).

Properties	Notation & Unit	Building elements
Density	γ (t/m ³)	2.5
Compressive stress*	f_c (kg/cm ²)	90
Tensile stress*	F_t (kg/cm ²)	10.8
Shear stress*	q (kg/cm ²)	19
Young's modulus	E (t/m ²)	2.1E06
Poisson's ratio	ν	0.20
compressive strain*	ϵ_c	0.003
tensile strain*	ϵ_t	0.003
Shear strain*	ϵ_s	0.003

*Allowable stress or strain.

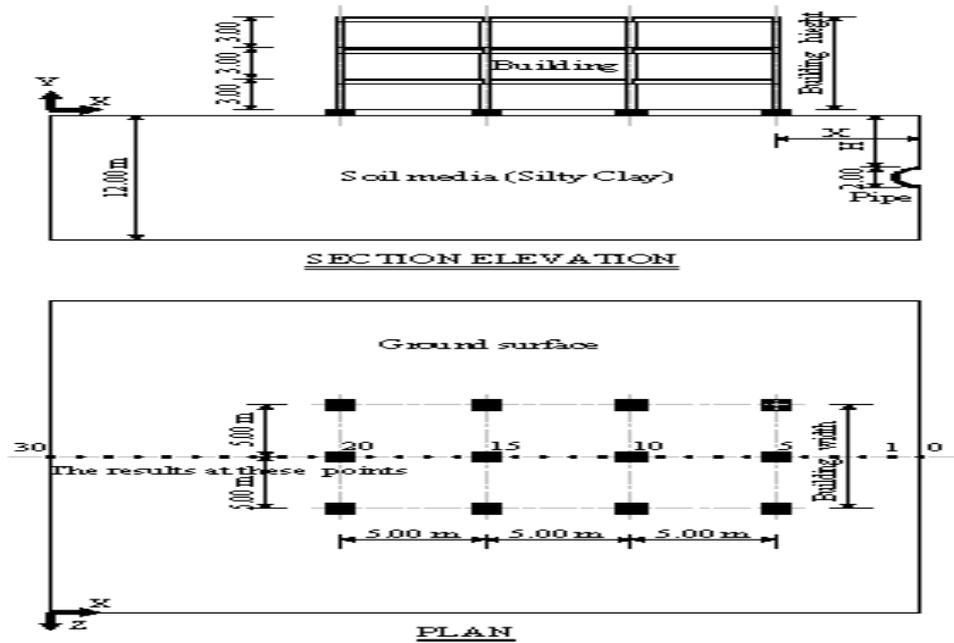


Figure 1 Geometry; (a) pipe-building-soil interaction geometry in the coupled analysis, (b) building geometry in the coupled analysis.

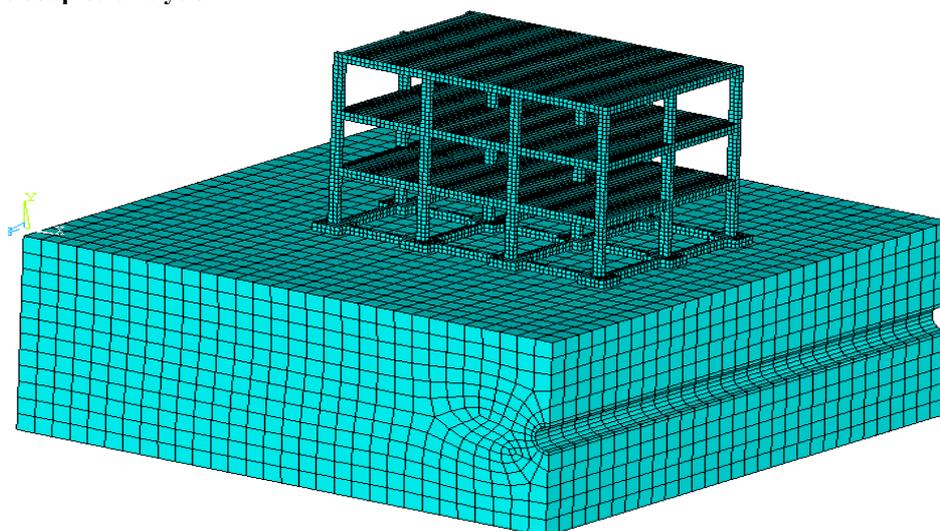


Figure 2 Finite element mesh adopted in the coupled analysis (R.C. building)

3. Parametric Study and Results:

Many variables affect the behavior of the system. Some of them are:

- Values of pipeline settlement.
- Position of settlement in pipeline relative to the building.
- Burial depth and pipeline settlement.
- Soil stiffness changing above pipeline.
- Sewage infiltration.
- Groundwater saturation.

The purpose of the coupled analyses (soil, pipeline and building in the same model) was to investigate the general mechanisms of soil structure interaction that occur in this type of problem. Each of these analyses produced a large amount of output data. This section highlights how the ground surface and building foundation displacement changes due to failure in pipeline. Figure 3 illustrates the place

(ground surface) of results (vertical settlements and horizontal displacements). The cumulative tensile crack width and cumulative principle crack width were calculated (Table 4) from the output displacement to assess the building condition. The calculations of tensile cracks were worked within spreadsheets. Damage categories are based directly on the descriptions of damage provided in the Table 1. In all data analyses, critical cracking strain was not included as a criterion (i.e. $\epsilon_c = 0\%$). The simple cumulative deformation was used directly considering that the buildings may have exhibited some initial cracking due to construction defects, thermal cracking, or from age. In addition, the calculation of tensile cracks were calculated at the first bay (from 5.0 to 10.0 m), where the first bay is the nearest place to the pipe failure.

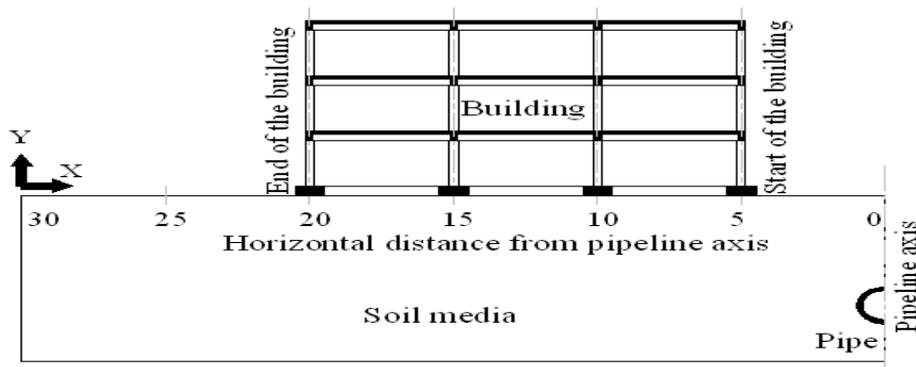


Figure 3 Schematic view of the model at place of results (displacements).

4. Effect of Pipe Settlement on Buildings:

4.1 Effect of value of pipeline settlement:

The influence of settlement in the pipelines is explained by considering three values of vertical settlement in the middle five pipes; 1% D, 3% D, and 5% D, where D is the pipe diameter. Tables 2 and 3 give the criteria of silty clay soil, pipe, and building

criteria respectively. Figures 4 and 5 show respectively the relations between the vertical and horizontal settlement of both ground surface and building (the building lies at distances from 5 to 20m from pipeline axis), and the pipeline settlement; we can find out that the minimum results are for minimum value of pipeline settlement.

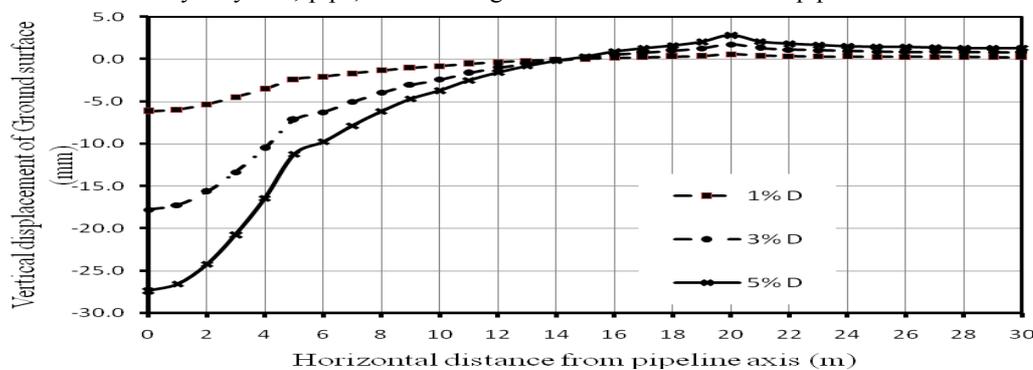


Figure 4 Effect of pipe settlement on vertical settlement of ground surface.

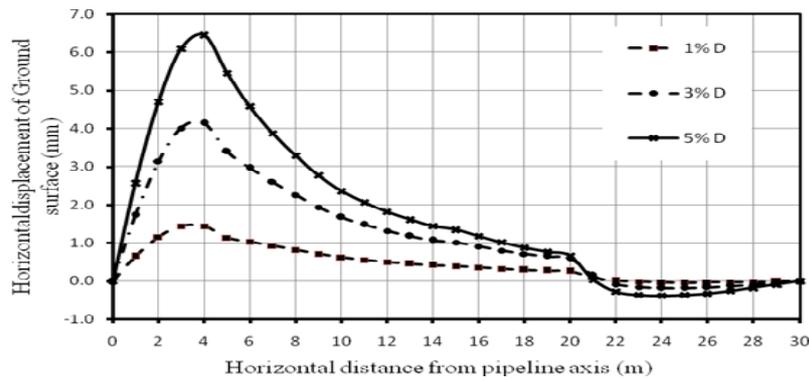


Figure 5 Effect of pipe settlement on horizontal displacement of ground surface

Table 4 illustrates the results for evaluating the potential damage category for in-fill walls and beams within frames due to different values of

pipeline settlement. The table shows the values of maximum and minimum vertical displacement, tilting angle α (Figure 6) for the base of building.

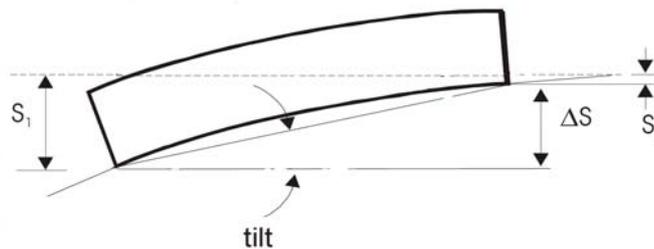


Figure 6 Definition of Tilting Angle α

Table 4: Evaluation of potential damage of building due to pipeline settlement

Properties	Case			Unit
	1% D	3% D	5% D	
Max. Settlement (S1)	-2.4	-7.2	-11.2	mm
Min. Settlement (S2)	0.6	1.8	2.8	mm
Differential Sett. (ΔS)	2.9	8.9	14.0	mm
Angle of Tilt α	0.011	0.034	0.054	deg.
Cumulative Tensile crack width (C_t)	0.74	2.39	4.11	mm
Cumulative Principle crack width (C_p)	0.77	2.37	3.84	mm
Damage Category	Very Slight(1)	Slight(2)	Moderate(3)	

The results presented in previous table show the effect of pipeline settlement on the value of α and the crack width, it is clear that the value of pipeline settlement plays an important role in building deformation and damage.

From the above, the major effect of the vertical settlement of pipeline on the increase of the deformations of adjacent buildings is within about 6 times the pipe diameter or two times of burial depth and slightly varying after this distance.

4.2. Effect of settlement location relative to the building

The influence of settlement location in the pipelines is explained by considering three locations from vertical axis of symmetry for vertical settlement in the five pipes ; B=0, B=1 and B=2, where B is the horizontal shift in the symmetric axis of pipes settlement and equals 3 times the pipe diameter. The

settlement value was taken 5% D (D is pipe diameter).

Figures 7 and 8 show respectively the relations between the vertical and horizontal

settlement of building and the horizontal location of pipeline settlement. From Table 5, we can find out that; the maximum results are for nearest location (B=0) of pipeline settlement.

Table 5: Evaluation of potential damage of building due to the settlement location.

Properties	Case			Unit
	B=2	B=1	B=0	
Max. Settlement (S1)	-1.1	-3.7	-11.2	mm
Min. Settlement (S2)	1.2	2.0	2.8	mm
Differential Sett. (ΔS)	2.2	5.8	14.0	mm
Angle of Tilt α	0.008	0.022	0.054	deg.
Cumulative Tensile crack width (C_t)	0.5	1.1	4.1	mm
Cumulative Principle crack width (C_p)	0.5	1.3	3.8	mm
Damage Category	Very Slight (1)	Slight (2)	Moderate (3)	

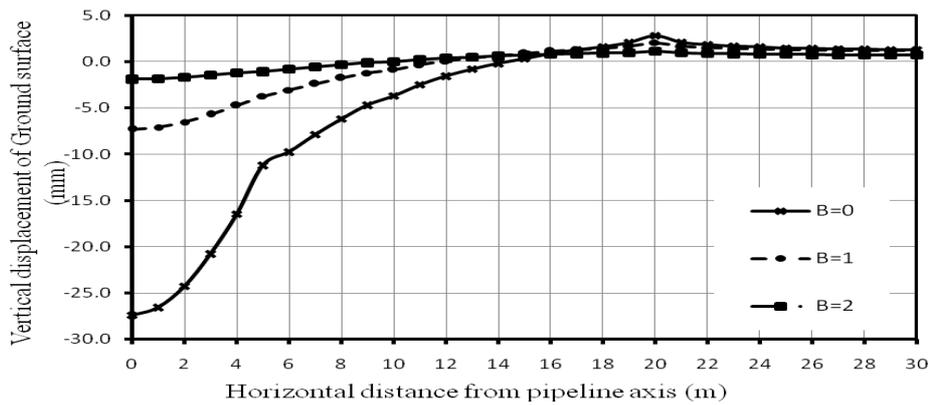


Figure 7 Effect of settlement location on vertical settlement of ground surface.

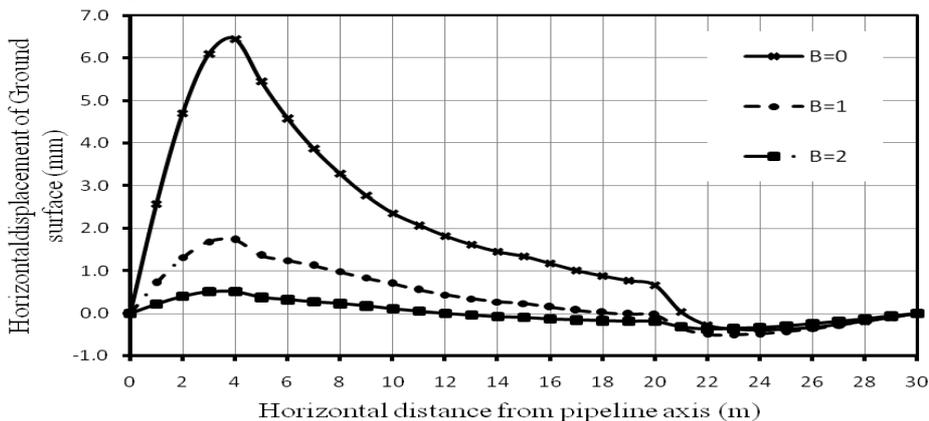


Figure 8. Effect of settlement location on horizontal displacement of ground surface.

4.3. Effect of burial depth

The effect of burial depth is demonstrated by considering three heights of soil above the pipe; 3,

5, and 7 m of silty clay soil. The settlement value was taken 5% D (D is pipe diameter).

Figures 9 and 10 illustrate the effect of burial depth and pipeline settlement on the vertical settlement and horizontal displacement of building;

we can notice that; increasing the height of soil above the pipe causes slight decrease in the building differential settlement.

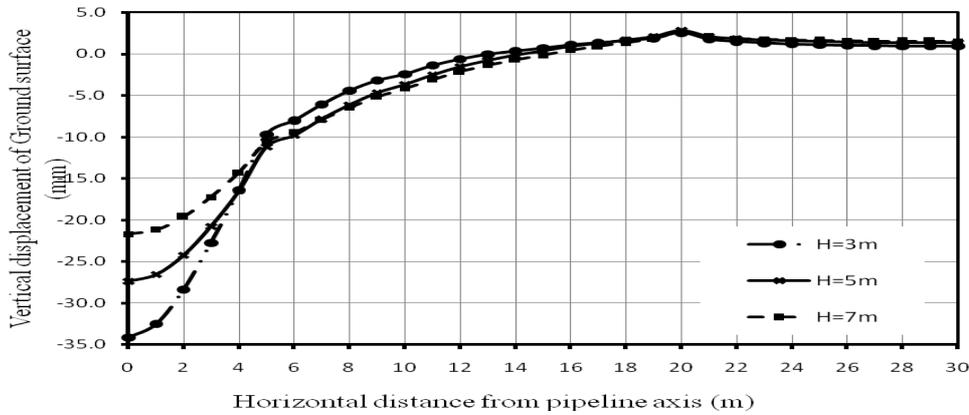


Figure 9 Effect of burial depth on vertical settlement of ground surface.

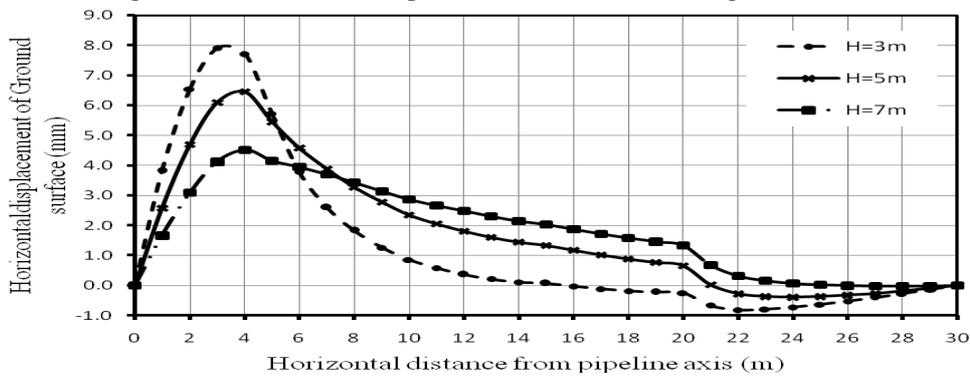


Figure 10 Effect of burial depth on horizontal displacement of ground surface.

From Table 6, we can find out that; the maximum results of building deformation and

damage are for smallest burial depth of pipeline settlement.

Table 6: Evaluation of potential damage of building due to burial depth of pipes

Properties	Case			Unit
	H=3m	H=5m	H=7m	
Max. Settlement (S1)	-9.7	-11.2	-10.6	mm
Min. Settlement (S2)	2.6	2.8	2.5	mm
Differential Sett.(ΔS)	12.3	14.0	13.1	mm
Angle of Tilt α	0.047	0.054	0.050	deg.
Cumulative Tensile crack width (C _t)	5.6	4.1	2.1	mm
Cumulative Principle crack width (C _p)	4.4	3.8	2.7	mm
Damage Category	Moderate (3)	Moderate (3)	Slight (2)	

5. Effect of the Soil Stiffness Changing Above Pipeline on Building

The case of soil stiffness changing above pipeline may takes place from the deteriorated pipeline. This case of deterioration may be failure in pipeline or separation of joints between pipes, which leads to soil infiltration to the pipes.

The influence of the soil stiffness changing above pipeline is explained by considering three values of soil stiffness for the part of soil, which it is above the pipeline. These values are relative to the

value of the existing soil stiffness; 0.25E, 0.50E, and 0.75E.

Figures 11 and 12 shows the relation between the vertical settlement and the horizontal displacement of building, and the soil stiffness changing above pipeline. From Table 7, we can find out that the building deformation and damage decrease with increasing the soil stiffness above the pipeline. In addition, the maximum results are from soil with relative stiffness 0.25E relative to the original soil.

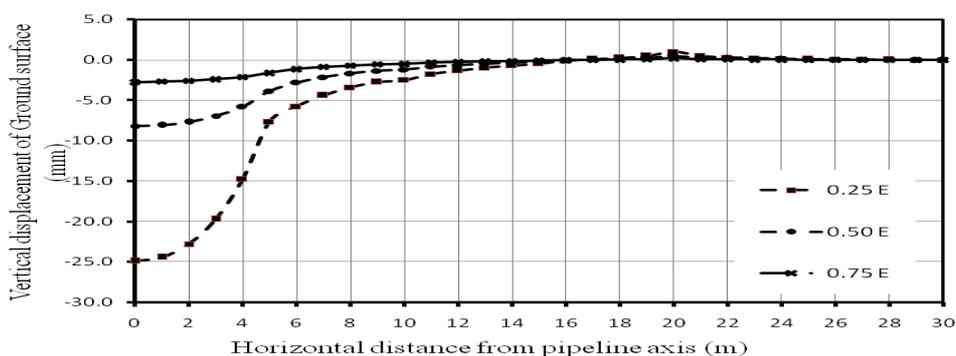


Figure 11 Effect of soil stiffness on vertical settlement of ground surface.

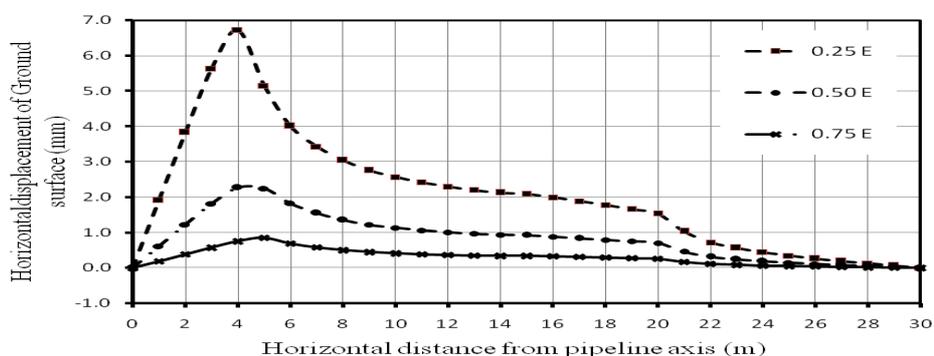


Figure 12 Effect of soil stiffness on horizontal displacement of surface.

Table 7 Evaluation of potential damage of building due to change of soil stiffness.

Properties	Case			Unit
	0.75 E	0.50 E	0.25 E	
Max. Settlement (S1)	-1.6	-3.9	-7.6	mm
Min. Settlement (S2)	-0.1	-0.2	-0.4	mm
Differential Sett.(ΔS)	1.5	3.7	7.2	mm
Angle of Tilt α	0.006	0.014	0.027	deg.
Cumulative Tensile crack width (C _t)	0.5	1.3	3.1	mm
Cumulative Principle crack width (C _p)	0.6	1.5	3.0	mm
Damage Category	Very Slight (1)	Slight (2)	Moderate (3)	

6. Effect of Sewage Water on Building

The influence of the sewage water around pipeline is explained by considering three areas with soil saturated with sewage water around the pipe. These areas are 3 circular rings around the pipe with thicknesses $D/2$, D and $3D/2$ respectively (figure 13), where D is the pipe diameter. Maaitah et al. (2005) have been concluded in their research that the raw

wastewater has a negative effect on the shear strength, compaction process and soil swelling. They reported the relationship between the degree of saturation and shear strength for soils that mixed with raw wastewater, treated wastewater and distilled water as show in Figure 14 where the effect of sanitary water on soil properties was illustrated (Ana, 2007).

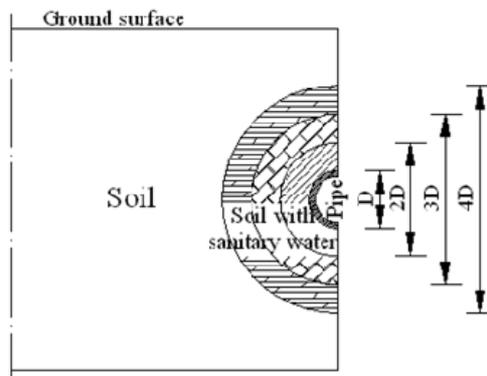


Figure 13 Schematic View of the Problem.

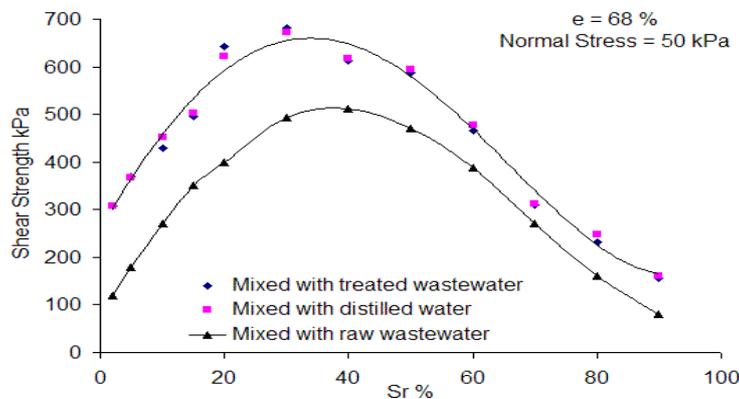


Figure 14 Unsaturated shear strength versus degree of saturation (Maaitah 2005).

Figures 15 and 16 shows the relation between the vertical settlement and the horizontal displacement of building and the saturated soil with wastewater around the pipeline. From Table 8, we

can find out that the building deformation and damage increases with increasing the area of sewage water around pipeline.

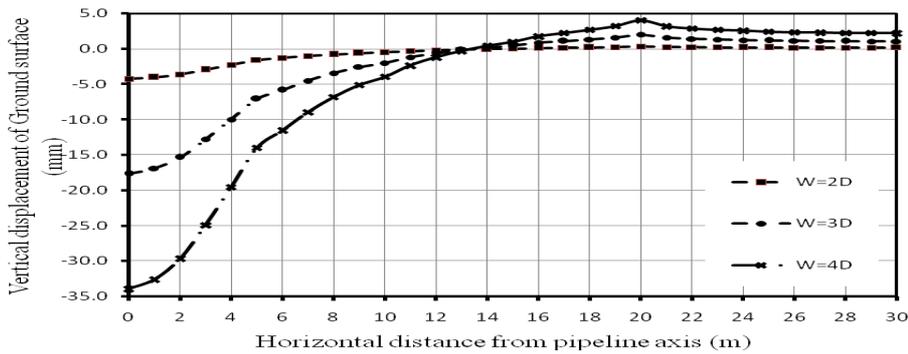


Figure 15 Effect of sewage water on vertical settlement of ground surface.

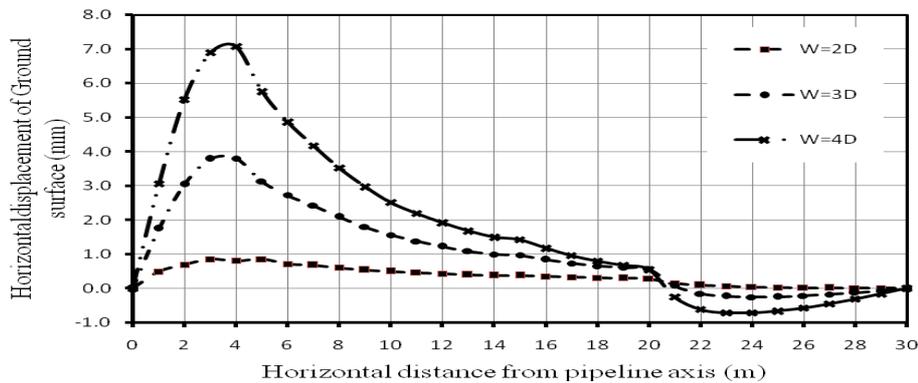


Figure 16 Effect of sewage water on horizontal displacement of ground surface.

Table 8: Evaluation of potential damage of building due to sewage water.

Properties	Case			Unit
	W=2D	W=3D	W=4D	
Max. Settlement (S1)	-1.6	-7.1	-14.0	mm
Min. Settlement (S2)	0.0	0.5	1.0	mm
Differential Sett. (ΔS)	1.6	7.6	15.0	mm
Angle of Tilt α	0.006	0.029	0.057	deg.
Cumulative Tensile crack width (C _t)	0.5	2.2	4.3	mm
Cumulative Principle crack width (C _p)	0.6	2.7	5.3	mm
Damage Category	Very Slight (1)	Slight (2)	Moderate (3)	

7. Effect of Groundwater on Building

The influence of groundwater is explained by considering three types of silty clay soil with different degrees of saturation; 50%, 70%, and 90%. The More-Coulomb parameters (cohesion) of the three soils are: 1.8, 1.0, and 0.5 t/m², respectively (AL-Shayea, 2001). In addition, the angles of internal friction for the three soils are 27, 16, and 8 degree (C-CORE, 2003). Figures 17 and 18 show the relation between the vertical settlement and horizontal

displacement of building and the degree of saturation in soil; we can find out that the minimum results are for 50% saturated soil relative to the saturated soil. In addition, due to large values of settlement the number of cracks is high which increases the category of damage even for very low differential settlement. From Table 9, we can find that the building deformation and damage increase as the groundwater saturation degree increases due to decrease in cohesion value.

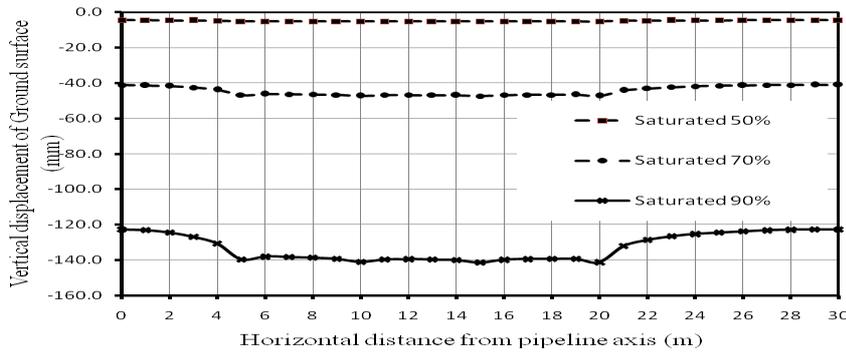


Figure 17 Effect of groundwater on vertical settlement of ground surface.

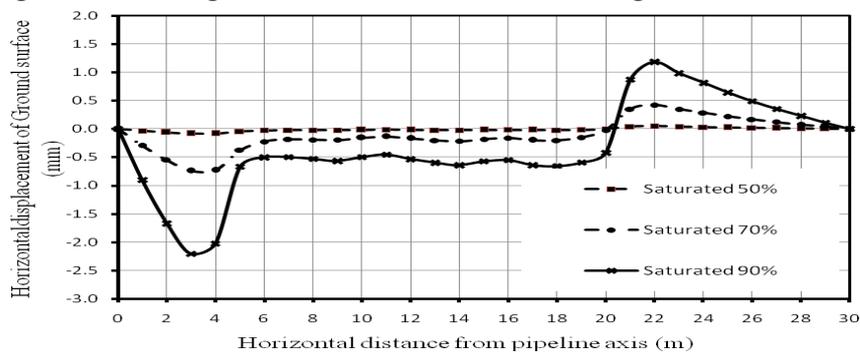


Figure 18 Effect of groundwater on horizontal displacement of ground surface.

Table 9. Evaluation of potential damage of building due to groundwater.

Properties	Case			Unit
	Saturated 50%	Saturated 70%	Saturated 90%	
Max. Settlement (S1)	-5.2	-46.8	-139.7	mm
Min. Settlement (S2)	-5.3	-47.3	-141.2	mm
Differential Sett. (ΔS)	-0.1	-0.5	-1.5	mm
Angle of Tilt α	0.000	-0.002	-0.006	deg.
Cumulative Tensile crack width (C_t)	0.0	0.0	0.0	mm
Cumulative Principle crack width (C_p)	0.0	0.3	0.6	mm
Damage Category	Slight (2)	Moderate (3)	Severe (4)	

8. Conclusion

We can conclude from results that the damage of adjacent buildings due to pipeline failure is increased by:

1. The increase of pipelines settlement and how near is its location.
2. The decrease of the position of settlement with respect to the building.
3. The decrease of soil stiffness above pipeline.

4. The increase of area of exfiltration of sewage water around pipelines.

5. The increase of the degree of soil saturation due to groundwater.

6. The decrease of burial depth of pipes.

The major effect of all above factors occurs within soil width equal about six times the pipe diameter or two times the burial depth from vertical axis of pipelines.

Therefore, this part of soil should be monitored on a regular basis for early prevention of buildings damage and pipeline deterioration.

The presence of building increases the soil stiffness in contact to the footings. That is why the rate of variation of displacement is decreased below the building.

Corresponding Author:

Dr. Manar M. Hussein

Lecturer in Structural Engineering Department,
Faculty of Engineering, Cairo University, Egypt

E-mail: manar.m.hussein@gmail.com

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