Damage assessment of buildings due to pipeline settlement using fuzzy decision support tool

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Abstract: Settlement of buildings, due to nearby pipeline deterioration can result in noticeable damage. By combining ground deformation patterns with well-known damage category criteria, the building deformations can be readily assessed without undue oversimplification. In this paper, the well-known computer program ANSYS with geotechnical module "CivilFEM" is used considering linear elastic soil behavior. The finite element model is chosen to investigate the influence of pipeline settlement and burial depth on possible damage of adjacent buildings. Thus, damage category of buildings can be predicted. Also, a fuzzy based assessment system, which evaluates the damage category of buildings was introduced. A criterion to define the membership functions of fuzzy assessment system starting from available information obtained from ANSYS was also described. This results in the prediction of the category of damage of buildings due to the interaction of more than one parameter in pipeline deterioration.

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1. Introduction

Due to the high interaction between pipelines deterioration and existing structures in urban areas, pipeline failure draws much attention. Therefore, the influence of pipeline failure on adjacent structures was very important to investigate.

A finite element computer program "ANSYS+CivilFEM"[1], which takes into consideration the elasto-plastic behavior of soil, the pipeline failure mechanisms, and the presence of the structure, was employed to perform the analysis and investigate the general failure mechanisms of soil-structure interaction. This analysis produced a large amount of output data. The paper highlights how the pipeline failure can induce vertical settlements of the foundation of the adjacent structure, which result in noticeable damage of buildings. The report by Aye [2] was used as a basic reference in ground deformation prediction and building damage assessment. For cut-and-cover excavation zone, the work of Peck [3], Clough [4] was used whereas published papers of Burland [5], Boscardin and Cording [6] were applied for bored tunnels. Also, Metwally [7] has evaluated the damage assessment of building due to deterioration of pipelines .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 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 aging. 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.

The analysis of the pipeline–structure interaction problem is performed with two steps. The first step (steady state) is concerned with the determination of initial stresses in the soil mass prior 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. The pipeline failure operation is modeled by settlement of the pipeline. The calculation of damage category by "ANSYS+CivilFEM" software is tedious and time consuming and it doesn't cover the entire operation range. Therefore, an expert system will be used to predict the degree of damage for different parameters of pipeline failure.

One of the most important applications of expert systems in engineering is fuzzy logic. The fuzzy set theory was developed by Lofty Zadeh [8] in 1965 to deal with imprecise and uncertain Phenomena often presented in real-world applications. It provides [9] a powerful tool for modeling uncertainty associated with vagueness, imprecision and lack of information.

Table 1. Building damage classification after Burland [5] and Boscarding and Cording [6].

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**

Consequently, fuzzy logic provides an efficient way of handling the uncertainty for complex systems without sufficient data or only with vague information [10-11]. The fuzzy controller has been used [12] for optimization of the active control of civil engineering structures [13-14-15-16-17]. The main advantages of the fuzzy controller are [14]:

- It is one of the few mathematical model free approaches to system identification and control which makes the system easier to design than developing an accurate mathematical model of the structural system needed for control system design. This can be done by using human experience and expertise to implement the fuzzy controller.
- It tolerates the uncertainties of the input data from wind or earthquake excitations and structural vibration sensors, consequently resulting in a controller system with a sufficient inherent robustness.
- The fuzzy controller can be adaptive by modifying its rules or membership functions and employing learning techniques.

In this study, a fuzzy rule-based decision support system is developed to determine the damage category of a building for a wide range of parameters, depending on crack width and number of cracks obtained from ANSYS model.

2. Fuzzy inference methodology

Fuzzy logic [9] is a kind of multi-valued logic utilizing fuzzy sets to perform approximate reasoning. Additionally, a fuzzy rule-based system is a methodology for the interpretation of natural language, which is essential for linguistic expressions. Fuzzy rules and fuzzy reasoning are the fundamentals of fuzzy inference processes that are utilized to derive meaningful conclusions from ambiguous information [11].

In this context, Fuzzy Inference Systems (FIS), also known as fuzzy rule-based systems, are well-known tools for the simulation of nonlinear behaviors with the help of fuzzy logic and linguistic fuzzy rules. There are currently several popular inference techniques developed for fuzzy systems, such as Mamdani and Assilian [18], and Takagi and Sugeno [19]. Mamdani FIS was selected to be used in this study. In the Mamdani FIS, inputs and outputs are represented by fuzzy relational equations in a canonical rule based form. These linguistic IF-THEN rules are associated with logical connectives, namely AND, OR, ELSE. For example, in the following expression in Eq. (1) the conjunctive (AND) is used as connectives in a fuzzy IF-THEN rule:

$$IF\ x\ is\ A^1\ AND\ A^2\ ...\ AND\ A^N\ THEN\ y\ is\ B^1 \quad (1)$$

Where: A and B are fuzzy sets with membership functions, μ_A and μ_B, calculated by a minimization procedure as shown in Eq. (2):

$$\mu_B i(x) = \min\,[\mu_A^1(x), \mu_A^2(x), ..., \mu_A^N(x)] \quad (2)$$

Analogously, disjunctive connectives are employed as follows:

IF x is A^1 OR A^2 ... OR A^N THEN y is B^1 (3)

and obtained membership function is given by a maximization procedure as:

$\mu_B i(x) = max\ [\mu_A{}^1(x), \mu_A{}^2(x), ..., \mu_A{}^N(x)]$ (4)

Another important point that should be explained about fuzzy rule-based systems is how the aggregation of fuzzy rules is performed. It is necessary to obtain an overall conclusion through a consideration of results from each rule. The combination of entire outcomes in a rule-base is referred as the aggregation of fuzzy rules. Similar to the association of fuzzy variables, there are two cases used in the aggregation process, namely conjunctive and disjunctive systems of rules [10-11]. A graphical representation of a Mamdani inference system with two rules and two crisp inputs is shown in Figure 1. The Mamdani fuzzy inference process gives a two-dimensional solution area, as can be seen in Figure 1. But it is necessary to obtain a single value instead of a region to reach a decision; therefore, the solution should be defuzzified to get a crisp outcome.

There are several methods developed for defuzzification process, such as centroid, weighted average, and center of sums. According to the centroid defuzzification method chosen in this research, a single output (*X**) in Eq. (5) can be calculated as follows:

$$X^* = \frac{\int \mu_A(x).xdx}{\int \mu_A(x)dx} \qquad (5)$$

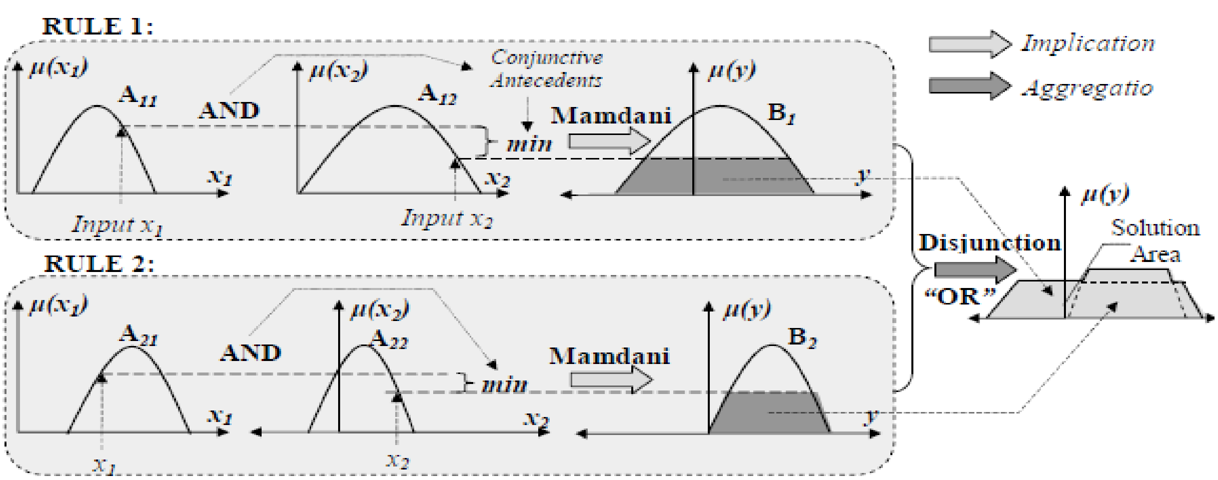

Fig. 1. Graphical illustration of Mamdani inference methodology (for two rules and two inputs) [9].

3. Description of basic model

Figures 2 and 3 depict the full three-dimensional geometry model which was used to quantify the interaction between sewer pipeline and the reinforced concrete building with masonry in-fill walls in the coupled analysis. The pipeline comprises 20 pipe segments, where the connections between them are contact element. The type of contact element of pipes connection was taken as "no separation contact element". In this "no separation contact" element, the two contact surfaces "target and contact surfaces" are tied, although sliding is permitted.

The pipeline is encased in a homogeneous, continuous, and isotropic soil mass. In addition, frictional slip is allowed between pipe and soil. The used data are shown in Table 2. The column's spacing of building in the two directions s = 5.0 m, and height of each level h = 3.0 m. The properties of structural materials taken for deformation and failure prediction calculations are shown in Table 3. 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.

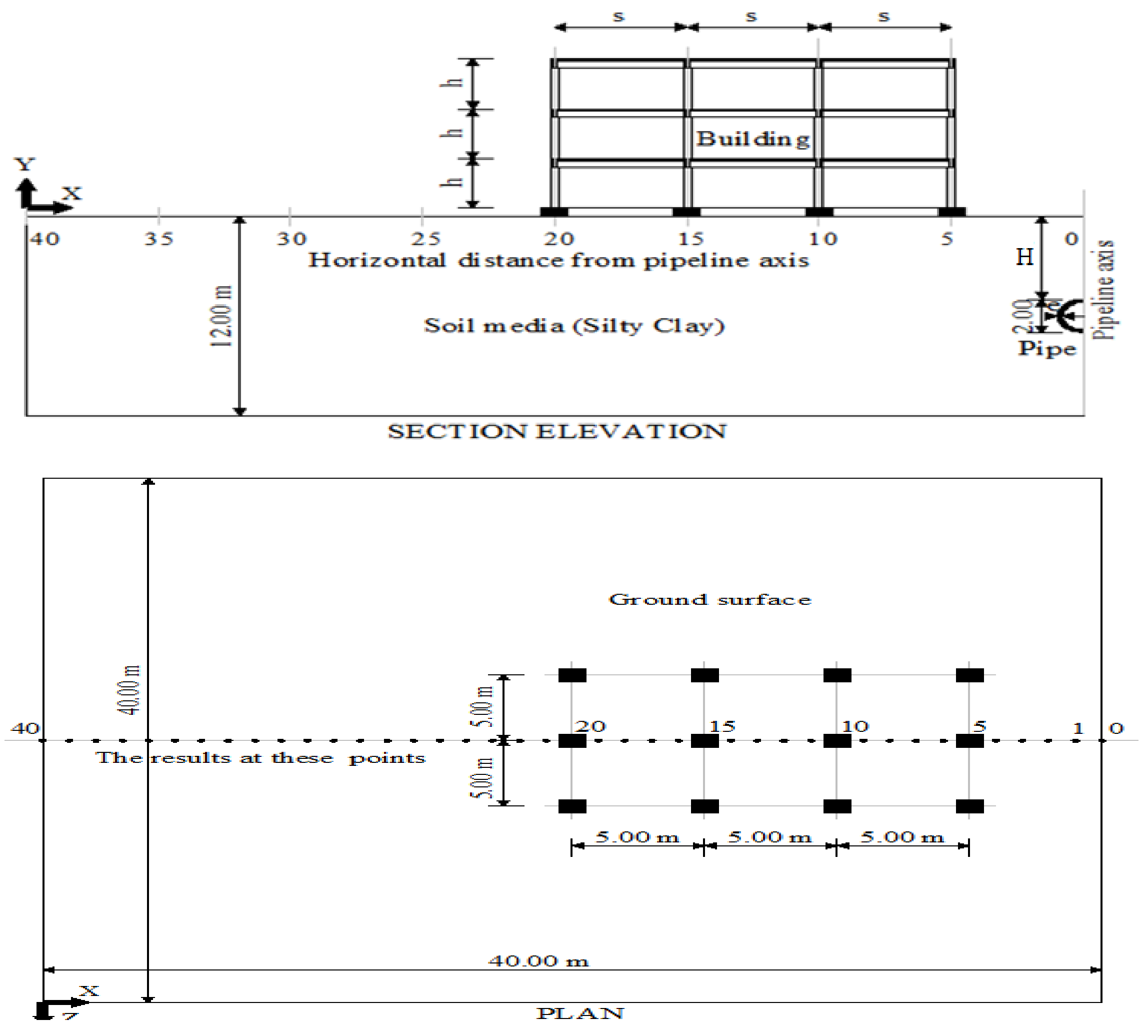

Fig. 2. Geometric model.

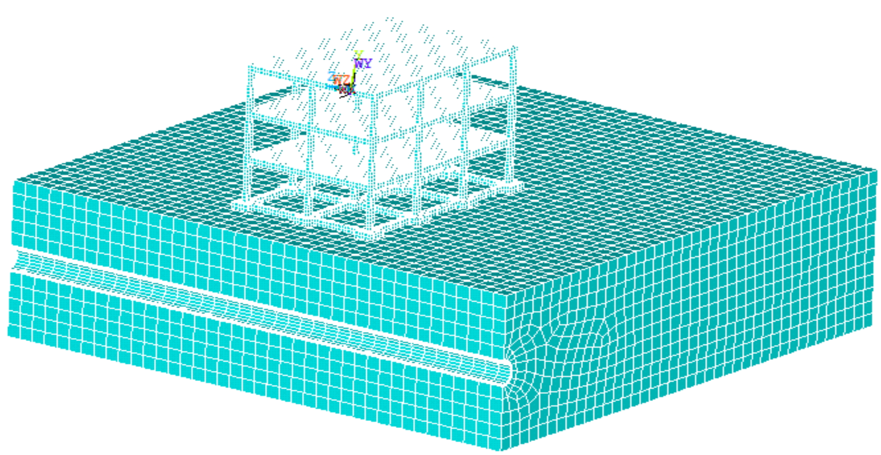

Fig. 3. FEM model.

Table 2. Soil and pipeline properties [7].

Soil properties		Pipeline properties	
Soil elastic modulus E_s	2000 t/m^2	Pipe diameter D (interior)	2.00 m
Soil Poisson's ratio υ	0.35	Wall thickness of concrete e	0.20 m
Soil cohesion C	2.00 t/m^2	Pipe length Lp	2.00 m
Angle of internal friction ϕ	30^o	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 υ_c	0.20
μ (Between soil& pipes)	0.32	μ (Between pipes segments)	0.60

Table 3. Structural material data [7].

Properties	Notation & Unit	Building elements
Density	γ (t/m^3)	2.5
Compressive stress*	f_c (kg/cm^2)	90
Tensile stress*	ft (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

4. Influence of pipeline deterioration on building performance

The damaging impact of pipeline settlement on building performance has been shown to be a major problem for urban areas due to high reconstruction and maintenance costs. The assumptions of parametric study of this part are deduced from the practical observations of the deteriorated sewer pipes within the Greater Cairo sewer network [7].

4.1 Influence of pipeline settlement on building

The influence of settlement in the pipelines is explained by considering three values of vertical settlement in the middle six pipe segments; 1% D, 3% D, and 5% D, where D is the pipe diameter. Figure 4 shows the relation between the vertical settlement of building and the pipeline settlement. It is apparent that increasing the vertical settlement of pipeline leads to the increase of the deformations of the adjacent building.

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 results presented in this table show the values of differential settlement, tilting angle α for the base of building and illustrate the influence of pipeline settlement on the value of crack width. We can find out that, the maximum building deformation and damage at the maximum pipeline settlement. It is clear that the value of pipeline settlement plays an important role in building deformation and damage.

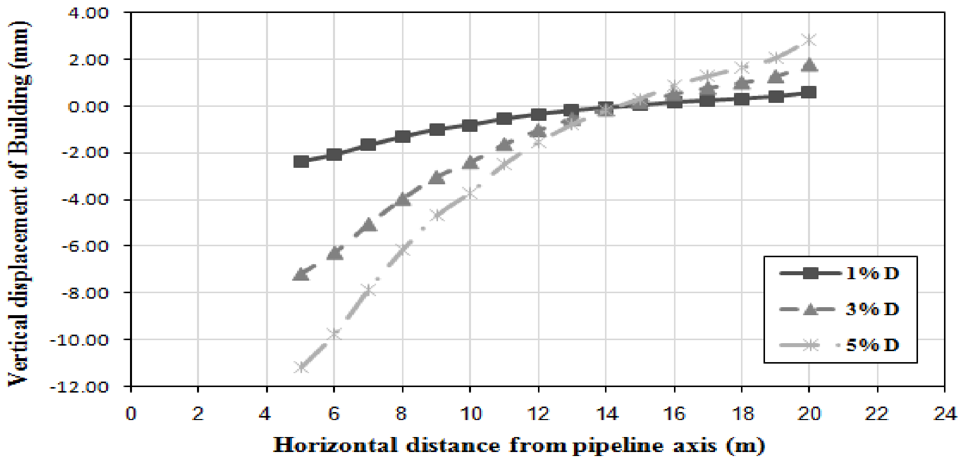

Fig. 4. Influence of pipeline settlement on vertical settlement of building.

Table 4. Evaluation of potential damage in building due to pipeline settlement.

Properties	Case		
	1% D	3% D	5% D
Differential Sett.(ΔS)	2.94	8.93	14.04
Angle of Tilt (α) rad.	0.00020	0.00060	0.00094
Cumulative Maximum Tensile Crack Width (C_t) mm	0.88	2.80	4.79
Cumulative Maximum Principal Crack Width (C_p) mm	0.81	2.50	4.06
Damage Category	Very Slight	Slight	Moderate

4.2 Influence of burial depth on building

The influence of burial depth is demonstrated by considering three heights of soil above the crown of the pipe; 3, 5, and 7 m. Tables 2 and 3 give the properties of silty clay soil, pipe, and building respectively. The settlement value was fixed as 5% D (D is pipe diameter) in the middle 6 pipe segments. Figure 5 illustrates the influence of burial depth and pipeline settlement on the vertical settlement of building. It is notice that increasing the height of soil above the pipe from 3m to 5m causes increase in building deformations.

Table 5 illustrates the results for evaluating the potential damage category for in-fill walls and beams within frames due to settlement in pipeline and different burial depth. The results presented in this table show the values of differential settlement, tilting angle α for the base of building and illustrate the influence of different burial depth with settlement in pipeline on the value of crack width. We can find out that, the maximum result of deferential settlement obtained from soil height above pipeline equal 5m. Also, the building damage is increasing by decreasing in the soil height above pipeline.

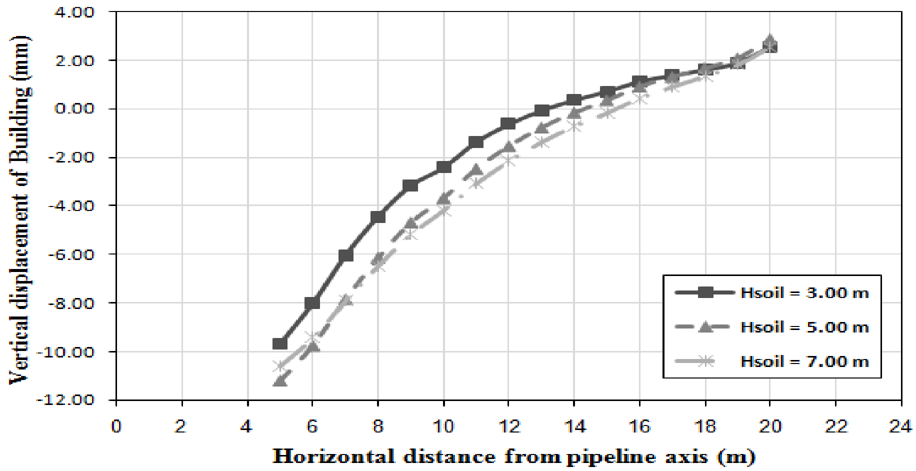

Fig. 5. Influence of burial depth on vertical settlement of building.

Table 5. Evaluation of potential damage to in building due to the burial depth value.

Properties	Case		
	H_{soil} = 3m	H_{soil} = 5m	H_{soil} = 7m
Differential Sett.(ΔS)	12.25	14.04	13.14
Angle of Tilt (α) rad.	0.00082	0.00094	0.00088
Cumulative Maximum Tensile Crack Width (C_t) mm	5.98	4.79	2.82
Cumulative Maximum Principal Crack Width (C_p) mm	4.55	4.06	2.92
Damage Category	Moderate	Moderate	Slight

5. Damage evaluation of building using fuzzy logic tool

One of the most important applications of fuzzy logic is that it can be used for decision process based on available data and knowledge. This study aims to construct a decision support system for damage category of reinforced concrete building structures based on numerical solutions obtained from ANSYS results for a wide range of parameters. Two different variables that have influence on building damage were used as inputs for fuzzy system. Then a procedure using the fuzzy inference methodology was developed to determine the output of a fuzzy system. The global structure of FIS component is depicted in Figure 6.

5.1 Fuzzification of pipeline settlement and burial depth

Fuzzy Logic Decision Support Tool (FLDST) is a control law that is described by a knowledge-based system consisting of IF . . . THEN rules with vague predicates and a fuzzy inference mechanism. The rule-base is the main part of the FLDST. It is formed by a family of logical rules that describes the relationship between the inputs (Pipeline Settlement (P.St) and Burial Depth (B.D)) and the output of the fuzzy system (Damage Category of building (D.C)).

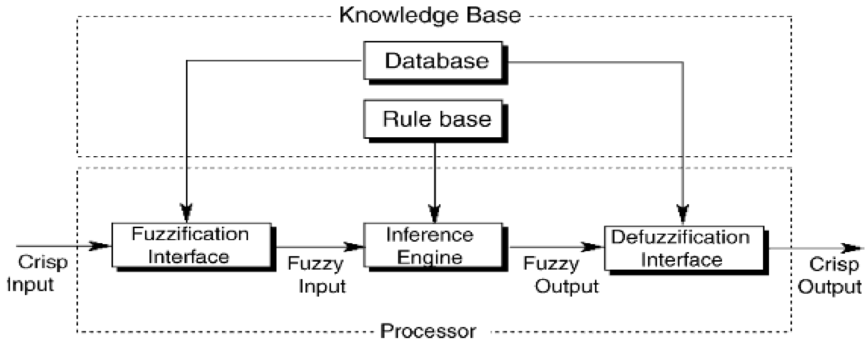

Fig. 6. Fuzzy inference system (FIS) component.

Based on the operator experience, the structure of the FLDST has two inputs and one output. Figure 7 illustrates the proposed structure of FLDST. These inputs are the Pipeline Settlement (P.St) and the Burial Depth (B.D). The data obtained from ANSYS as shown at figure 4 describes the influence of pipeline settlement on vertical settlement of building. We extended the influence of pipe settlement to 10%D and predicted damage at different values of settlement. Five Membership Functions (MFs) are chosen for the first input (pipeline settlement) where the outer right MF is S function, the outer left is Z function, and the inner three MFs are represented by triangle function as shown in figure 8.a. The linguistic terms for defining the membership functions are: (1%D), (3%D), (5%D), (7%D), and (10%D), where %D is percentage of settlement occurs as a function of pipeline diameter.

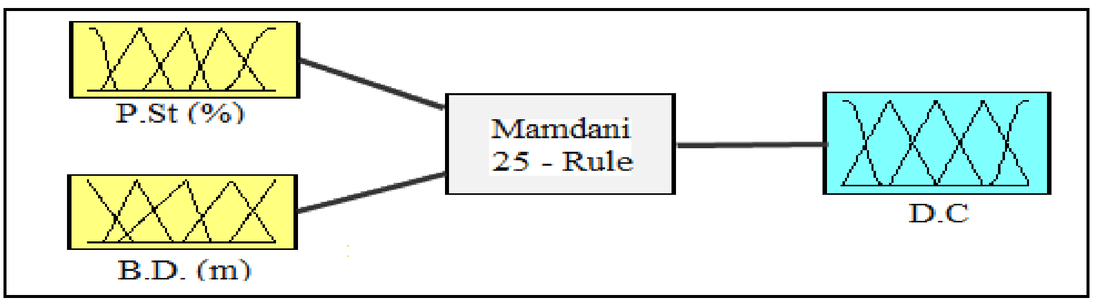

Fig. 7. Structure of FLDST: 2 inputs, 1 output and 25 rules.

The universe of discourse for the second input of FLDST (burial depth) is chosen from 3m to 7m. A five triangle membership functions are chosen to represent linguistic variables of MF and it's defined as (3m), (4m), (5m), (6m), and (7m) as shown in figure 8.b. Finally five membership functions are used to represent the five linguistic variables of output (damage category), the inner three MFs are triangle, the right MF is S function and the left MF is Z function, the name of five linguistic variables of output are: NEG is negligible, VSL is very slight, SL is slight, MOD is moderate and SV is severe as shown in figure 8.c.

5.2 Defuzzification of pipeline settlement and burial depth

Once the membership functions and the rule-base of the FLDST are determined, the final process of the FLDST is to aggregate the fuzzy sets resulting from the inference mechanism to produce a decision (i.e. crisp output), which is the "most certain" in respect of the current system behavior. A number of methods can be used for defuzzification (e.g. center-average, mean-of-maxima), however the most commonly used method is the equation for computation of center-of-gravity (COG), or centroid, which ensures a smooth control action but which requires more complex calculations particularly for non-linear MFs. The membership function for two inputs and single output is shown at figure 8. The 25 rule base was constructed based on data obtained from ANSYS results are shown in Table 6.

Figure 9 illustrates the surface of 25 rules for input MFs and output MFs in three-dimensions.

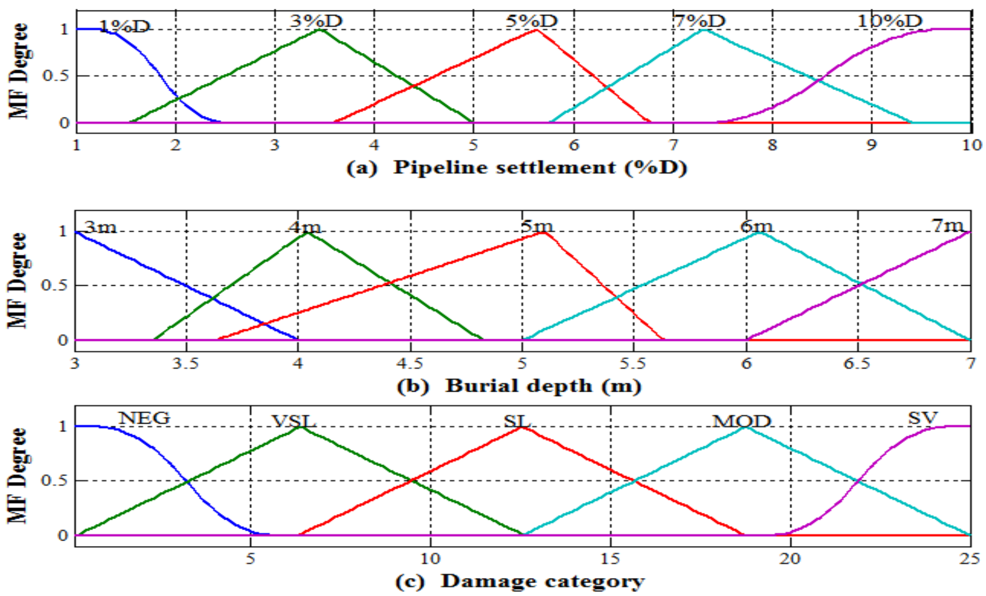

Fig. 8. Membership functions inputs (a), (b) and output (c) of FLDST.

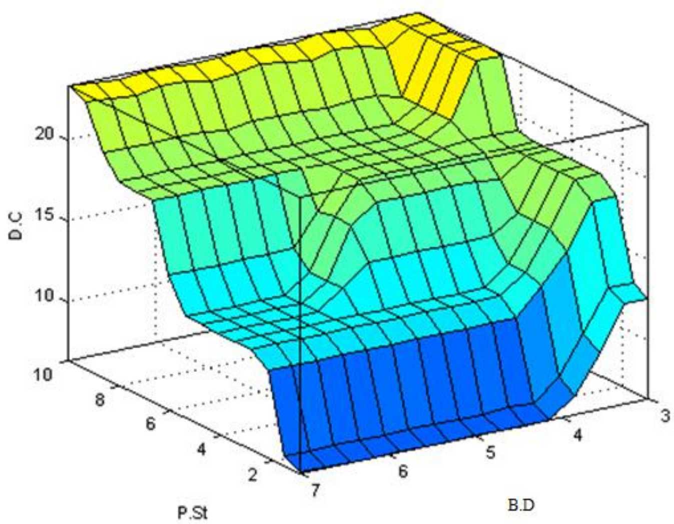

Fig. 9. Surface of 25 rules in three-dimensions.

Table 6. Fuzzy rule base.

		Pipeline Settlement				
		1%D	3%D	5%D	7%D	10%D
Burial Depth	H_{soil} = 3m	SL	MOD	MOD	SV	SV
	H_{soil} = 4m	VSL	SL	MOD	MOD	SV
	H_{soil} = 5m	VSL	SL	MOD	MOD	SV
	H_{soil} = 6m	VSL	SL	SL	MOD	SV
	H_{soil} = 7m	VSL	SL	SL	MOD	SV

5.2 Validation of results

Several examples were run by ANSYS for different pipeline settlement along with different burial depths. The category of damage was similar to the proposed method. Table 7 illustrates several examples from MATLAB that was validated by ANSYS computer program to validate and evaluate the proposed FLDST in evaluating the damage category of building. The damage category of building based on FLDST is consistent with that obtained from ANSYS calculations.

Table 7. Evaluation of potential damage due to different pipeline settlement along with different burial depths.

	Pipeline Settlement		Burial Depth		Damage Category
IF	2%D	AND	3.0m	THEN	SL
	2.5%D		4.5m		SL
	5%D		7.0m		MOD
	6.5%D		2.5m		MOD
	9%D		6.5m		SV

6. Conclusions

The purpose of this study is to present a method for evaluation of the damage category of building due to different parameters of pipeline failure. We chose here two parameters, pipeline settlement and burial depth. It can be concluded from this research that the building deformation is increased due to increase of pipeline settlement, and the increases of the height of soil above the pipeline. Also, the building damage is increased due to increase of pipeline settlement, and the decreases of the height of soil above the pipeline.

The fuzzy decision support tool was constructed for two inputs (pipeline settlement and burial depth) to get the total influence of these two variables on building damage. Moreover, the FLDST has the ability to cover the entire range of pipeline settlement and the burial depth. Accurate results were predicted based on FLDST for wide range of values of pipeline settlement and burial depth. Results were consistent to that obtained from ANSYS calculations.

For future work, it is possible to design similar fuzzy decision support tool for more than two parameters that affect pipeline failure, thus damage of building.

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