ARTICLE | **OPEN ACCESS**

Indian journal of
Engineering

Evaluation of static slope stability methods, regarding areas with buried gas pipelines, sewerage and cable networks

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To Cite:
Papageorgiou G, Paschalis E, Alamanis N, Chrysanidis T, Zahos D. Evaluation of static slope stability methods, regarding areas with buried gas pipelines, sewerage and cable networks. *Indian Journal of Engineering*, 2025, 22, e6ije1696
doi: https://doi.org/10.54905/disssi.v22i57.e6ije1696

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Peer-Review History
Received: 07 November 2024
Reviewed & Revised: 11/November/2024 to 29/March/2025
Accepted: 03 April 2025
Published: 11 April 2025

Peer-Review Model
External peer-review was done through double-blind method.

Indian Journal of Engineering
pISSN 2319–7757; eISSN 2319–7765

DISCOVERY
SCIENTIFIC SOCIETY

ABSTRACT

Across the world, there are areas susceptible to slope instability, probably due to their slope angle. It is well-known that, unfortunately, a large number of natural gas pipelines, sewerage and cable networks pass underground through these aforementioned areas making them vulnerable due to the possible slope instability. Occurrences of ground slides may lead to soil rupture, where the aforementioned networks could be located, especially in areas subjected to large-scale substructure projects, including foundations for buildings, highways, and railways, even large-scale infrastructure such as bridges and dams. On each slope, the difference in level and in slope inclination in combination with the gravitational forces and the possible presence of table water, eventually create shear stresses. Fortunately, these shear stresses are countered by the soil's shear resistance. When the developing stresses overcome shear resistance, then they lead to a rupture of the slopes and finally to a landslide. The instability of slopes, leading to the displacement of soil mass downstream known as landslide, constitutes a significant risk to human (social, economic and travel) activities. Specifically, the slope instability could result to injury and loss of life and property destruction. Moreover, the landslides could produce ground displacement, leading to a critical situation for power supply and urban waste water networks, resulting in energy loss and complete failure. Designing large construction projects in urban and suburban areas focuses on evading locations that are most-susceptible to geohazards. This approach has generally been successful when there are limited restrictions on selecting a pipeline route.

Keywords: Sewerage Network; Slope Stability; Infrastructure Stability Assessment; Estimation Methodologies; Energy Pipeline Failure

1. INTRODUCTION

Seismic codes along with material building regulations (e.g. concrete codes, steel codes, etc.) demand the appropriate design of structures and frameworks above and below ground in accordance with their provisions for the structural safety under static and seismic actions. The weak structural point for gas and oil pipes is ground movements such as soil liquification and slope displacement that may wreak a havoc on a pipeline system. As a result, the most important aspect of pipeline construction is a thorough analysis of soil qualities and probable reactions. As a matter of fact of the aforementioned condition, unmanageable fuel loss occurs, which is contrary to the energy saving principle.

In other words, oil and gas pipelines that are damaged lead to energy loss (Yokel and Mathey, 1992). Consequently, several approaches have been devised in order to accurately estimate such displacements. Fellenius, Bishop, Taylor, Finite Element Method (FEM) and Finite Difference Method (FDM) are examples of methods for determining static slope displacements. The Fellenius approach, often known as the Swedish Circle Method, is possibly the most extensive used method at stability analysis. The normal force on each slice in this manner is supposed to equal to the vertical component of that slice's weight. State that safety factors that are determined by using Fellenius approach could contain significant faults.

They highlight the way pore-water pressures are included into studies, as well as the calculated N values is another source of error (Cruikshank, 2002). Another method is the Bishop, which is commonly used for circular shear surfaces. This method takes under consideration the interslice normal forces but skips the interslice shear forces. It satisfies vertical force equilibrium to determine the effective base normal force N (Sangeeta and Maheswari, 2016). Additionally, Taylor series method describes the reliability of the slope by the factor of safety of slope stability. The corresponding factor of safety is calculated in accordance with different types of slopes. People think that the slope is stable as long as the factor of safety is larger than the target factor of safety.

The method of Taylor could potentially use the average value of each parameter for the determination of the safety factor, resulting to the estimation of the standard deviation of parameters, computing the standard deviation and coefficient of variation of the factor of safety and calculating the probability of failure by the most likely distribution of the factor of safety (Pan and Ma, 2013). FEM with two key applications has been developed for analysing slope stability. The first application tries to accomplish an elastoplastic analysis by applying to the slope system the body force due to the soil. After that, the second application has to do with the application of the Mohr-Coulomb criterion in order to calculate the local factors of safety.

The FEM has been employed to assess slope stability and evaluate slope stability during seismic loading (Azimi, 2016). One of the most important advantages of FEM is that the safety factor arises from the study without the need for any further calculations (Bray and Travasarou, 2011). Finally, Finite Difference Methods (FDMs) are useful tools since they can provide approximate solutions to the boundary value problems for partial differential equations. They fulfil all requirements that have to be met for a complete solution to the slope stability problems (Abdellah et al., 2018). The preceding approaches for static slope displacement are considered in this article, and then the AHP (analytical hierarchy process) is used to determine which is the most useful.

Furthermore, precise estimation of static slope displacement saves energy by reducing the risk of damage to the gas or oil pipeline network. Huang suggested a modified and improved version of typical Fellenius method, providing important information in terms of the displacement of slopes due to internal or external environmental changes. That form of Fellenius could satisfy force and movement equilibrium criteria from the initial slice method in combination with more displacement compatibility requirement and a soil pattern of hyperbolic shear stress displacement (Huang, 2019). Hajiazizi et al., (2018), introduced a prototype three-dimensional limit equilibrium method which uses the force and movement equilibrium equations and 3D slices along the slip surface radius converging to one point.

That method is less accurate than finite element method, however it gives larger FS compared to other equilibrium methods (Hajiazizi et al., 2018). Huang et al., (2014), modified a force-equilibrium-based finite displacement method in terms of force and movement equilibrium that derived from Bishop and Fellenius methods. They finally turned out that Bishop's method of limit equilibrium is proposed for application in FFDM (Huang et al., 2014). Baba et al., (2012), compared FEM, Fellenius and Bishop methods according to a real geometrical model, in order to calculate the FS. They concluded that Bishop's results are the nearest to those obtained by FEM (Baba et al., 2012).

Sahoo and Shukla, (2019), tried to evolve a detailed formulation taking under consideration both vertical and horizontal forces in order to calculate the safety factor of equivalent, cohesive-frictional soil slopes with ordinary profiles through Taylor's stability charts. Steward et al., (2011), proposed two different charts, one for undrained clays and a second one for drained. The one for undrained clays uses different from the chart that Taylor proposed. The main point of the proposed charts is the presence of compound circles which consists of two distinct arcs connected with a straight line at the interface with the stiff stratum. Wang and Lin, (2021), combined a two-dimensional FEM analysis method with the fuzzy statistical method.

They reached the decision that fuzziness of mechanical parameters of rock and soil slope could lead to the fuzziness of position displacement as well as the stress analysis of slope. Pathak et al., (2008), tried to represent the gradual failure by the usage of a modified FEM method. This method allowed for the incorporation of time evolution. Furthermore, utilizing probabilistic principles, the influence of uncertainty in soil characteristics was investigated. Fu et al., (2021) simulated bi-axial and tri-axial geogrids with the coupled discrete element method (DEM) and finite difference approach (FDM). The pullout simulation results reveal that the DEM-FDM approach is more accurate than the DEM method in predicting the relationship between pullout force and displacement.

As a result, the DEM-FDM coupled approach can be used to not only examine the interlocking mechanism between ballast and particles, but also to evaluate the performance of various geogrids. In terms of technique evaluation, Saaty developed the AHP approach as an effective multifactor procedure that is widely recognized since it has a wide variety of applications in engineering projects (Delgado et al., 2014; Macedo and Candia, 2020). This methodology has been adopted by many researchers in identical studies. Luo et al., (2016) combined the AHP and entropy weight method for the slope stability of the open pit mines. By using the AHP, they determined the weight of factors and by using the entropy method, they calculated the influence factors.

El-Jazouli et al., (2019) created a landslide susceptibility map of the Oum Er Rbia high basin through the AHP method in order to evaluate land cover, lithology, distance to road, distance to fault, distance to drainage network, elevation, aspect and slope gradient, considering that they influence the displacement occurrence. Parsakhoo and Hosseini, (2013) applied the AHP method in order to evaluate the most appropriate earthwork machine like bulldozers and excavators according to criteria such as cross section, grade line, production rate, production cost, soil displacement and multiplication. Grozavu et al., (2017) investigated a plateau zone in Eastern Romania in relation with landslide susceptibility. The landslide inventory, the digital elevation model and the thematic layers of few factors like topographic characteristics, land utilization and rock type determination, were evaluated through the AHP.

Komac, (2006) investigated a landslide distribution with a combination of two methods, the factor analysis (FA) and the multiple regression analysis (MRA). Their results were used in AHP which it was composed of two models. The model with the best results was used in purpose of detecting areas that are prone to landslide occurrence. Tairi et al., (2019) sketched out a map of areas with high risk of water erosion in Tifnout-Askaoun, Marocco, while used the AHP method. They tried to determine the vulnerability of the soil to erosion, according to factors such as slope, density of drainage, land occupation, soil erodibility and the erosion potential of rain. Applicability, advantages and limitations of the above presented static slope stability methods, are summarized in (Table 1).

Table 1 Applicability, advantages, and limitations of different static slope stability methods

Static slope displacement determination methods	**Applicability**	**Advantages**	**Limitations**
Fellenius	√	Most easily applicable	Not indicated in case of high precision analysis necessity
Bishop	√	Ideal for circular shear surfaces	Not indicated in case of high precision analysis necessity
Taylor	√	Most inclusive in terms of probabilistic factors	-
FEM	√	Most Accurate	-
FDM	√	Most Accurate	Specialized personnel requirements

2. METHODS

Predicting seismic slope displacements shows great complicity with a variety of factors that affect accuracy, including: ease and rate of application, range of application, and the completeness of methods. Modern investigations Alamanis and Dakoulas, (2020a) indicate that transient ground motion of an embedded pipeline in an earth slope may not cause plastic strains on the pipe, if there is no slope failure. This is attributed to the fact that the pipeline flexibility allowed by the two elbows may accommodate small ground movements. By contrast, if the slope experiences failure followed by large displacements (due to strong shaking and small soil strength), the pipe may experience severe global and local buckling.

The complex situation should be reviewed from all points of view, in terms of engineering criteria. Designers, field constructors and engineers should be specialists in all available technologies, in order to reach the most accurate results, which could decrease the possibility of slope displacements during an earthquake, particularly for slopes penetrated by gas and oil pipelines. Better results lead to less slope displacement and greater energy saving through avoiding such incidents. After all the aforementioned, Figure 1 displays the most suitable method which is the AHP procedure with a single branch approach. The aspects of such an evaluation are, subsequently:

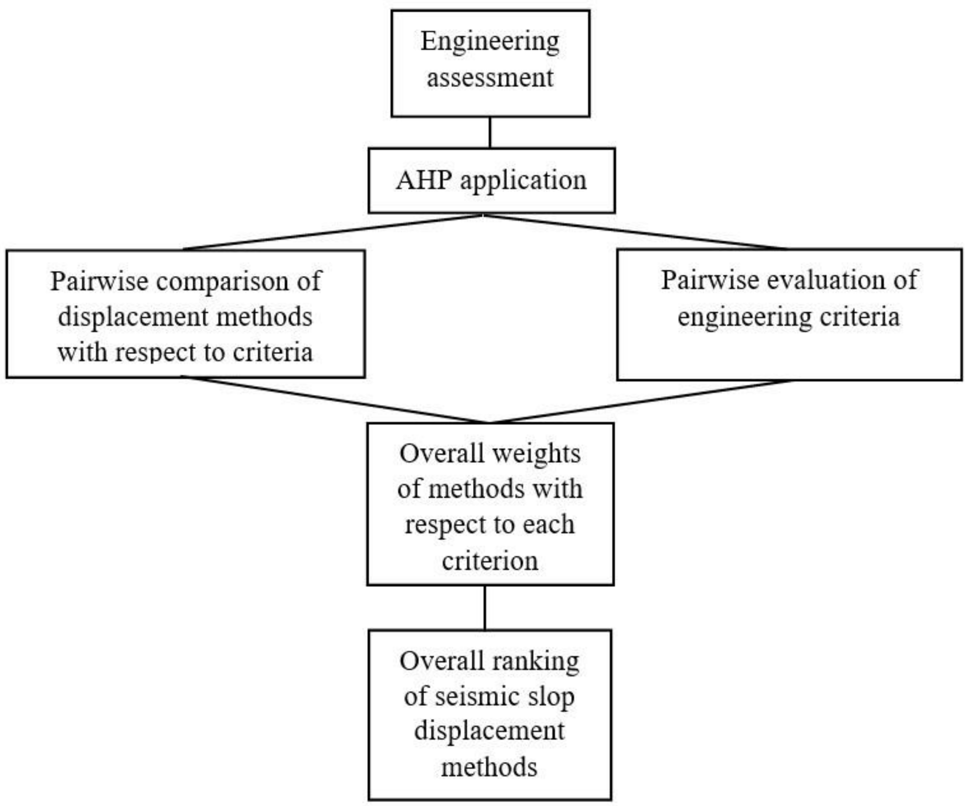

Figure 1 Flowchart of the proposed concept

In particular, this assessment includes the following steps:
Application of AHP for engineering evaluation;
Description of engineering criteria;
A pairwise comparison of seismic displacement methods with respect to each criterion;
A pairwise comparison between engineering criteria;
Weights are determined in terms of seismic displacement method;
Ranking of each method, according to each criterion, and overall results.

The seismic performance of oil and natural gas steel pipelines embedded in earth slopes presents great uncertainty related both to the earthquake shaking characteristic sand to the natural heterogeneity of geomaterials. Because they have the potential to permanently distort and burst pipes, causing spills, environmental issues, and extended outages, slope movements and landslides in general pose a serious risk to pipelines. Moreover, significant risks for underground pipeline integrity may be caused by permanent ground displacements from tectonic fault action, lateral spreading of liquefied soils, where soil can move for a few meters and impose major deformation on the section of pipeline passing through the affected area. Similar risks appear also in the case of pipes embedded in a liquefiable soil layer passing below a river or ground aquifer. In all these cases, the pipe may be subjected to bending resulting to significant compression, with a high risk of local buckling, large plastic deformation and wall rupture.

3. RESULTS AND DISCUSSION

Figure 2 displays the aforementioned method executed with criteria extracted from the previous study, while the distribution of criteria for engineering classification are shown by (Table 2).

Table 2 Description of engineering evaluation criteria

Engineering criteria	Description
Accuracy	Accuracy of results, deviation from the actual values of the stability factor
Ease and rate of application	Degree of application of each method and the ease of application in practice, i.e. the required time and any specialised software
Range of application	The scope of application and the impact of each method in international practice
Completeness	Completeness of results in the most reliable application due to more data being considered

Table 3 Engineering evaluation of seismic slope displacement methods

Method of seismic slope displacement	Accuracy	Ease and rate of application	Range of application	Completeness
Fellenius	Fair	Fair	Fair	Fair
Bishop	Fair	Low	Low	Low
Taylor	Low	Fair	Low	Low
Finite Element Method	High	High	Very High	High
Finite Difference Method	Very High	High	Very High	High

In Table 3, the evaluation of the methods consists of the scale: low, fair, high, very high or excellent. The important part is the scaling difference between them, after the harmonisation with the fundamental scale for pairwise comparisons (Saaty, 1990). In Figure 2, the AHP hierarchically models the problem. After a series of pairwise comparisons between the boxes in the flowchart, the priorities are formed. A pairwise comparison occurs with respect to their contribution to the previous criteria. The mathematical procedure of the AHP generates the priorities for all nodes on a level (Saaty, 1990). Table 4 shows the fundamental scale introduced by (Saaty, 1990).

Table 4 Fundamental scale for pairwise comparisons (Saaty, 1990)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment moderately favour one element over another
5	Strong importance	Experience and judgement strongly favour one element over another

7	Very strong importance	One element is favoured very strongly over another, its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation

* Intermediate values to reflect compromises: 2, 4, 6, 8

** Values for inverse comparison: 1/3, 1/5, 1/7, 1/9

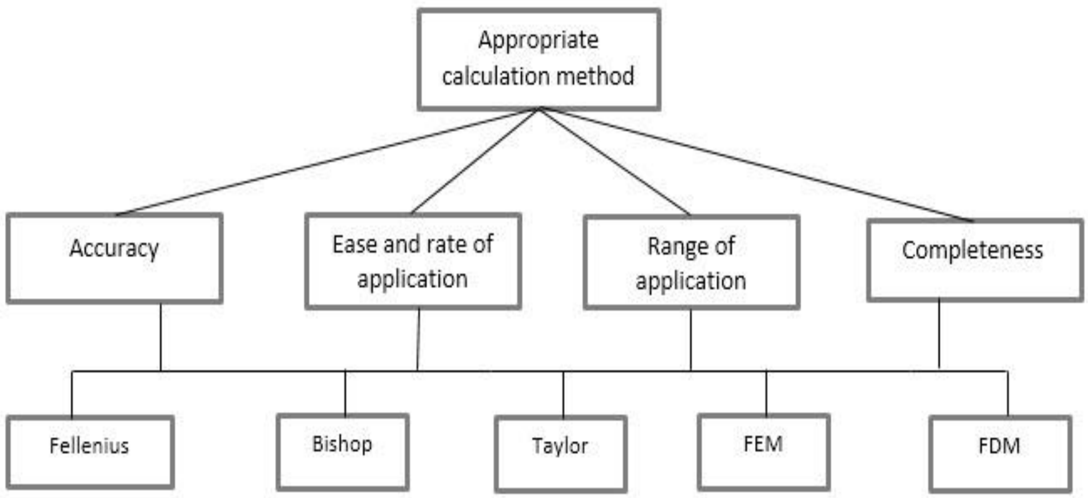

Figure 2 The hierarchy for evaluation of static slope stability methods

AHP application for engineering sub-criteria

Table 5 presents the comparative relationships of the seismic slope displacement methods with respect to each criterion. The consistency ratios for pseudo-static, Newmark and numerical analysis pairwise comparisons are 4.0%, 4.0%, 6.8%, and 3.0%, respectively.

Table 5 Pairwise comparison of methods with respect to the engineering criteria

Accuracy	**Fellenius**	**Bishop**	**Taylor**	**FEM**	**FED**	**Priority**
Fellenius	1	1	3	1/3	1/5	0.102
Bishop	1	1	3	1/3	1/5	0.102
Taylor	1/3	1/3	1	1/5	1/7	0.046
FEM	3	3	5	1	1/3	0.245
FED	3	5	7	3	1	0.504
Ease and rate of application						
Fellenius	1	3	2	1/2	1/2	0.178
Bishop	1/3	1	1	1/3	1/3	0.086
Taylor	1/2	1	1	1/5	1/5	0.074
FEM	2	3	5	1	2	0.377
FED	2	3	5	1/2	1	0.285
Range of application						
Fellenius	1	3	3	1/2	1/3	0.171
Bishop	1/3	1	2	1/3	1/4	0.088
Taylor	1/3	1/2	1	1/5	1/6	0.055

FEM	2	3	5	1	1/2	0.266
FED	3	4	6	2	1	0.421
Completeness						
Fellenius	1	3	3	1/2	1/2	0.200
Bishop	1/3	1	1	1/3	1/3	0.088
Taylor	1/3	1	1	1/4	1/4	0.077
FEM	2	3	4	1	1	0.318
FED	2	3	4	1	1	0.318

Thereafter, Table 6 shows the pairwise comparison of the criteria, with respect to their potential to achieve the best option, with a consistency ratio of 0.8%.

Table 6 Pairwise comparison matrix of engineering sub-criteria with respect to reaching the goal

Engineering criteria	**Accuracy**	**Ease and rate of application**	**Range of application**	**Completeness**	**Priority**
Accuracy	1	3	5	2	0.502
Ease and rate of application	1/3	1	2	1	0.192
Range of application	1/5	1/2	1	1	0.123
Completeness	1/2	1	1	1	0.183

Table 7 Weights of engineering sub-criteria according to seismic slope displacement method

Criterion	**Static slope stability method**	**A**	**B**	**C**
Accuracy	Fellenius	0.102	0.502	0.051204
	Bishop	0.102		0.051204
	Taylor	0.046		0.023092
	FEM	0.245		0.122990
	FED	0.504		0.253008
Ease and rate of application	Fellenius	0.178	0.192	0.034176
	Bishop	0.086		0.016512
	Taylor	0.074		0.014208
	FEM	0.377		0.072384
	FED	0.285		0.054720
Range of application	Fellenius	0.171	0.123	0.021033
	Bishop	0.088		0.010824
	Taylor	0.055		0.006765
	FEM	0.266		0.032718
	FED	0.421		0.051783
Completeness	Fellenius	0.200	0.183	0.036600
	Bishop	0.088		0.016104
	Taylor	0.077		0.014091
	FEM	0.318		0.058194
	FED	0.318		0.058194

Table 7 shows the weights of the engineering criteria conforming to the displacement evaluation methods, where column A is filled with priorities after pairwising the slope displacement procedures with engineering criteria (Table 4). Column B shows the priority of each criterion with respect to the goal (Table 5) and column C shows the result of the two weights with respect to the goal. Table 8 presents the overall weights for every displacement method in relation to every criterion.

Table 8 Overall weights of slope displacement techniques from engineering scope

Seismic displacement method	Priority with respect to				
	Accuracy	Ease and rate of application	Range of application	Completeness	Goal
Fellenius	0.051204	0.034176	0.021033	0.036600	0.1430
Bishop	0.051204	0.016512	0.010824	0.016104	0.0946
Taylor	0.023092	0.014208	0.006765	0.014091	0.0582
FEM	0.122990	0.072384	0.032718	0.058194	0.2863
FED	0.253008	0.054720	0.051783	0.058194	0.4177

AHP application for resources' restrictions

The application of the AHP method, from an economic point of view, is a critical point of such an evaluation, since it affects the choice of any methodology. Taking into consideration the fact that designing a structure could take place in a country with very low finances, then the most profitable method would be the most economic. According to this restriction, there is a pairwise comparison between engineering criteria, with regards to their cost. Therefore, in consonance with the fundamental scale in Saaty, (1990) (Table 4), and considering that ease and rate of application has the greater weight, the completeness is the next most-important, then accuracy and, finally, the range of application. In agreement with the previous turn the first criterion means the cheapest one and the fourth comes with the most expensive. A pairwise comparison of the engineering criteria, with regards to the cost, is given in Table 9, with a consistency ratio of 6.3%

Table 9 Pairwise comparison matrix of engineering sub-criteria with respect to reaching the financial potential

Engineering criteria	Accuracy	Ease and rate of application	Range of application	Completeness	Priority
Accuracy	1	1/9	2	1/3	0.042
Ease and rate of application	9	1	3	7	0.501
Range of application	1/5	1/3	1	1/3	0.046
Completeness	3	5	3	1	0.410

Table 10 Weights of engineering sub-criteria with regard to financial potential, according to the seismic slope displacement method

Criterion	Static slope stability method	A	B	C
Accuracy	Fellenius	0.102	0.042	0.004284
	Bishop	0.102		0.004284
	Taylor	0.046		0.001932
	FEM	0.245		0.010290
	FED	0.504		0.021168
Ease and rate of application	Fellenius	0.178	0.501	0.089178
	Bishop	0.086		0.043086
	Taylor	0.074		0.037074
	FEM	0.377		0.188877

	FED	0.285		0.142785
Range of application	Fellenius	0.171	0.046	0.007866
	Bishop	0.088		0.004048
	Taylor	0.055		0.002530
	FEM	0.266		0.012236
	FED	0.421		0.019366
Completeness	Fellenius	0.200	0.410	0.082000
	Bishop	0.088		0.036080
	Taylor	0.077		0.031570
	FEM	0.318		0.130380
	FED	0.318		0.130380

Table 10 shows the priorities of engineering criteria in line with the displacement assessment techniques, where column A is filled with priorities after pairwising slope displacement procedures with respect to engineering criteria (Table 5). Column B shows the priority of each criterion according to the financial cost (Table 9) and column C shows the result of the two priorities with respect to the goal. Table 11 presents the overall priorities for every displacement methodology in relation to each criterion.

Table 11 Overall weights of slope displacement techniques from engineering scope (based on financial restrictions)

Seismic displacement method	Priority with respect to				
	Accuracy	Ease and rate of application	Range of application	Completeness	Goal
Fellenius	0.004284	0.089178	0.007866	0.082000	0.1833
Bishop	0.004284	0.043086	0.004048	0.036080	0.0878
Taylor	0.001932	0.037074	0.002530	0.031570	0.0730
FEM	0.010290	0.188877	0.012236	0.130380	0.3417
FED	0.021168	0.142785	0.019366	0.130380	0.3137

Appraisal results

Using the previous results from the use of the AHP method, the subsequent stage is dependent on the stream diagram of the proposed idea (Figure 1) and creates tables ranking the seismic displacement methods, after classifying the priorities of engineering criteria, with regard to cost. Hence, in the Tables 12 and 13, is presented the ranking of each method according to each engineering criterion, as well as the overall ranking of the procedures taking into account the economic factor. Afterwards, there are two bar diagrams (Figures 3 and 4), each for every appraisal, in order to provide a holistic view of assessments with respect to each criterion and overall.

At last, a composite evaluation is the amount of the design and methodology assessment results increased by weight factors. Consequently, the forthcoming outcomes of the AHP approach for the optimal selection of seismic displacement methods may yield more precise designs, thereby reducing pipeline failures and enhancing energy savings. However, the financial situation of each country plays a significant role.

Table 12 Overall engineering ranking of seismic displacement methods according to financial factors

Seismic displacement method	Ranking in terms of accuracy	Ranking in terms of ease and rate of application	Rankings in terms of range of application	Ranking in terms of completeness	Overall ranking
Fellenius	3	3	3	2	3
Bishop	3	4	4	3	4

Taylor	4	5	5	4	5
FEM	2	1	2	1	2
FED	1	2	1	1	1

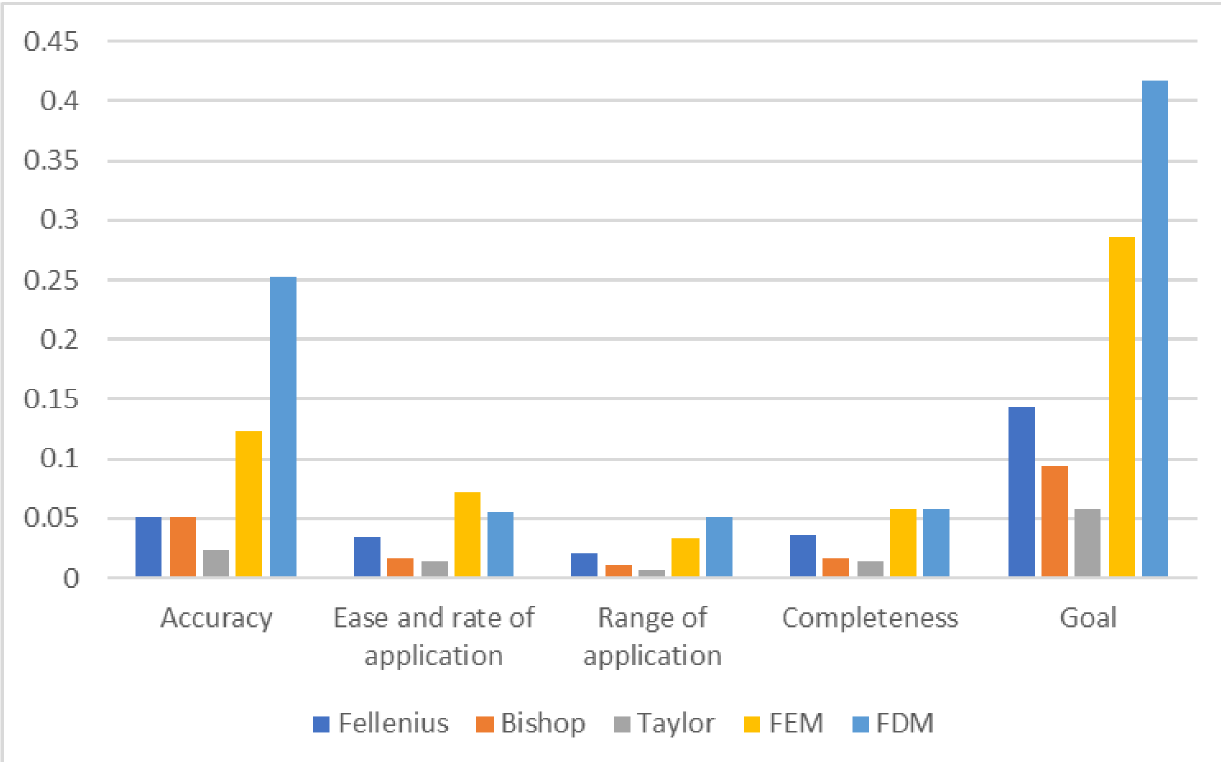

Figure 3 Holistic view of evaluation with regard to every criterion and overall (no resource restrictions)

Table 13 Overall engineering ranking of seismic displacement methods

Seismic displacement method	Ranking in terms of accuracy	Ranking in terms of ease and rate of application	Rankings in terms of range of application	Ranking in terms of completeness	Overall ranking
Fellenius	3	3	3	2	3
Bishop	3	4	4	3	4
Taylor	4	5	5	4	5
FEM	2	1	2	1	1
FED	1	2	1	1	2

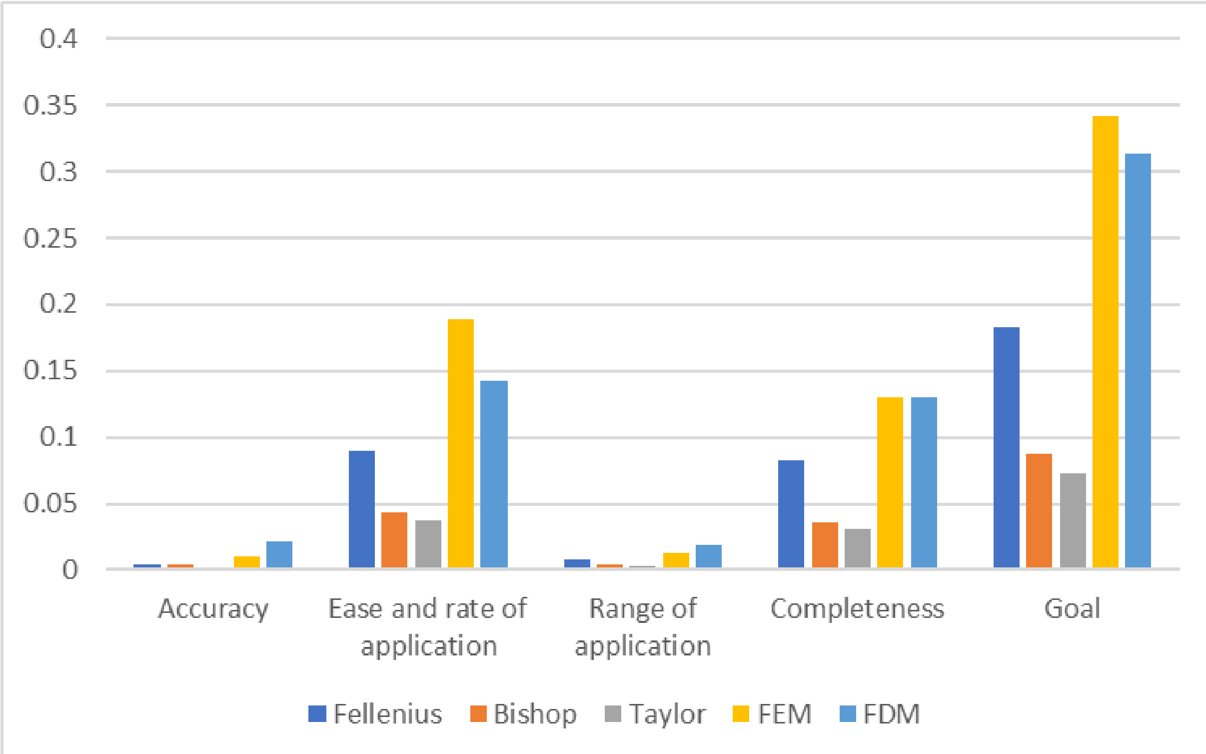

Figure 4 Holistic view of evaluation with regard to every criterion and overall (with resource restrictions)

Discussion

Honegger et al., (2010) investigated the failure conditions of pipelines stressed by landslides or more generally by soil uncertainties, while Marinos et al., (2016) investigated the areas of potential landslides at natural gas pipeline crossing points. Similarly, Vazouras et al., (2010) used the finite element method to identify failures in steel pipelines stressed by permanent slope movements. Similar is the work of Ariman, (1983), which monitors the deformations of pipelines due to large ground movements, and finally the work of Alamanis, (2020b), which studies the effect of spatial soil variability on the seismic vulnerability of slopes containing oil and gas pipelines.

However, it must be emphasized that none of the above works includes the use of the well-known and accepted AHP (analytical hierarchy process) method, thanks to which we reached important conclusions in the submitted study. However, it must be emphasized that none of the above works includes the use of the well-known and accepted AHP (analytical hierarchy process) method, thanks to which we reached important conclusions in the submitted study. Other useful conclusions that distinguish the present work from those mentioned in the literature are also derived.

4. CONCLUSIONS

One of the main targets of this study is the production of a device for designers and constructors, to provide options for reaching the optimal method for predicting seismic slope displacement, contingent upon the engineering factors. The proposed methodology consists of a proposal of all accessible choices. Hence, it is relatively simple to assess all dynamic options. Pseudo-static, Newmark and numerical analysis demonstrated their potential, in terms of accuracy, ease and rate of application, range of application and completeness. Numerical analysis showed its superiority regarding accuracy, range of application, completeness and the overall assessment. The accuracy percentage is doubled using the Newmark method and multiplied by four using the pseudo-static method.

The great range of potential applications makes this method widely applicable. In relation to completeness, it has proven its distinct difference against the other methods. On the other hand, the pseudo-static method is only ahead in terms of ease and rate of application because of its simplicity and so it is commonly used. The most profitable method, according to engineering criteria, is the numerical analysis because it is the most accurate procedure in predicting seismic slope displacement. On the other hand, after posing economic restrictions through engineering criteria, we can clearly see that the pseudo-static method overwhelms the others, in terms of ease and rate of application. Despite its inferiority to the other criteria, this method finally manages to keep ahead in the overall ranking. It is clarified that economic factors can affect the selection of a method in a moderate way.

Recommendations

Numerous techniques exist for enhancing seismically vulnerable soils, with the most prevalent being compaction, stabilization, and drainage approaches. Specifically, all aforementioned procedures are applicable to non-cohesive soils (sands, silts, gravels, or their combinations), whereas stabilization and compaction by gravel piles are employed in cohesive soils (soft clays, organics). The implementation of gravel piles will significantly enhance the consolidation degree and safety features of the completed structure and its ultimate consolidation. The proposed safeguards that fall in the category of immediate rehabilitation and are considered mild intervention, regard retaining structures, extensive excavations and formation of new slopes with low inclinations, using vegetation cover.

In addition, the biological engineering methods used both for the protection and stabilization of the slopes are environmentally friendly, limiting interference in environmentally sensitive areas. In accordance with the opinion of the authors of this article, the burden of environmental protection must be shifted from rehabilitation, to the prevention of failures, so that the environmental impact assessment shall be made in advance, based on the environmental design of slopes and engineering in general. In the context of practical recommendations for engineers, policy-makers and urban planners, some interesting information are included below:

As it is already mentioned, static or dynamic loads may constitute a threat for the structural integrity of buried pipelines. When permanent ground deformation is applied on the pipeline, a certain damage appears. Especially in case of slope instability during ground motion, which cause large permanent horizontal and vertical movements, the pipeline may be subjected to global and local buckling suffering a significant compression as shown in the (Figures 5-7).

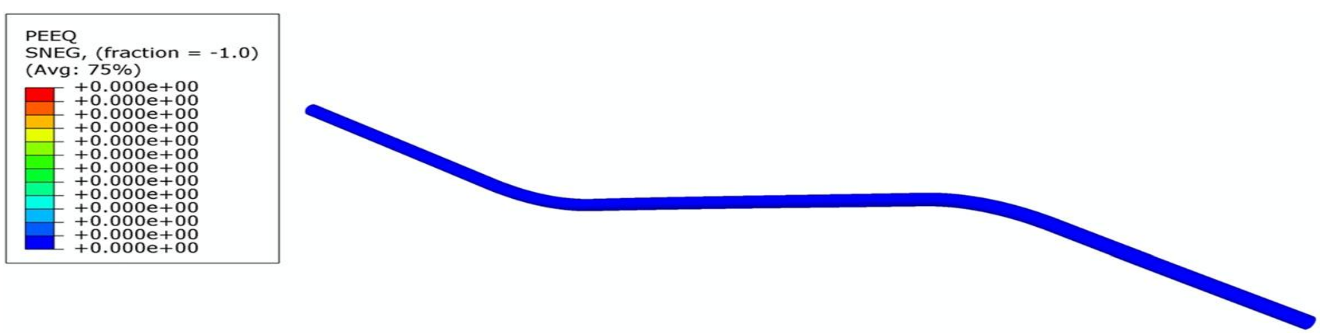

Figure 5 Elastic response of the pipeline without slope failure (Alamanis, 2020b)

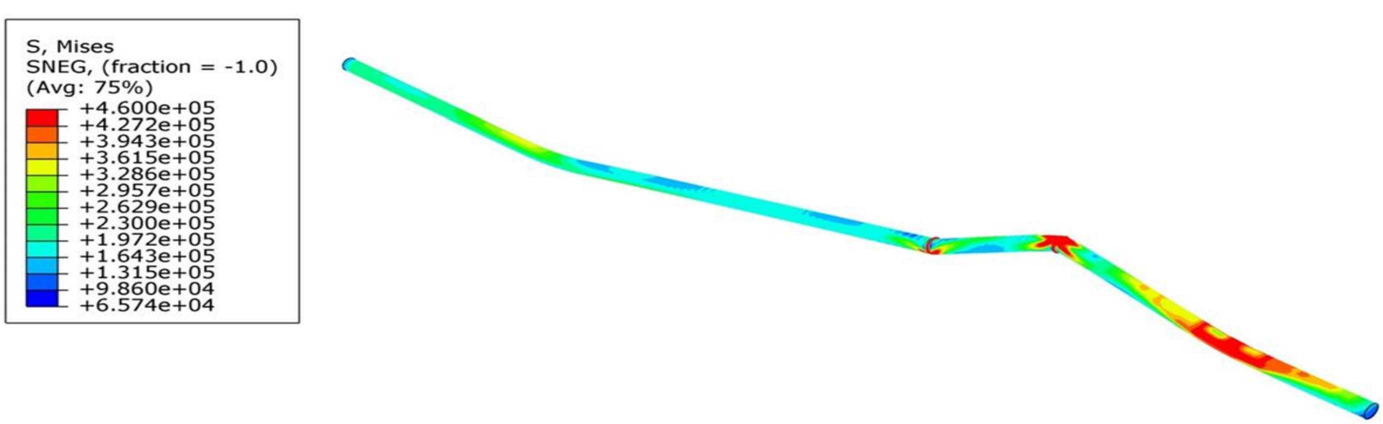

Figure 6 Global and local buckling of the pipeline during shaking in case of slope instability (Alamanis, 2020b)

The investigations have also shown that the spatial variability of soil properties play an important role for the behavior of buried infrastructures, because the imposed ground motion may depend significantly in a zone along the path of the pipeline system. In conclusion, along the route of buried pipelines, the area must be checked with extensive geotechnical investigation, especially when the slopes are subjected to static or dynamic loads.

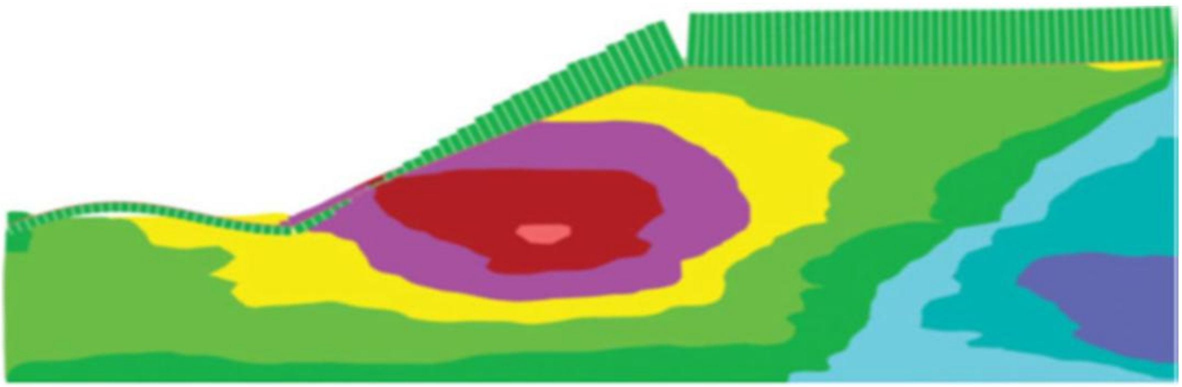

Figure 7 Distribution of compressive stresses along the pipeline causing global and local buckling in the section of the pipeline on the slope toe. Also, distribution of permanent horizontal displacement of the soil mass at the end of shaking (Alamanis, 2020b)

Acknowledgement
We thank the participants who were all contributed samples to the study.

Author Contributions
Author 1: Conceived and designed the analysis, Wrote the paper
Author 2: Wrote the paper
Author 3: Collected the data
Author 4: Contributed data
Author 5: Wrote the paper

Informed consent
Not applicable.

Ethical approval
Not applicable.

Funding
This study has not received any external funding.

Conflict of Interest
The author declares that there are no conflicts of interests.

Data and materials availability
All data associated with this study are present in the paper.

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