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Additional Information

Strategic decision support system for utility tunnel's planning applying A'WOT method

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Abstract

Future sustainable underground strategies will consist of the ability to reduce overcrowding subsurface space in our cities. To this end, utility tunnels become a key factor in urban underground planning. These facilities improve joint-use of urban underground space (UUS) that may contain multiple utilities such as water, sewerage, gas, electrical power, telephone, and central heating in several combinations or in some cases all together. However, implementing these subsurface tunnels is retarded most by first-cost, compatibility, security and liability problems. All these drawbacks should be addressed in early planning stages taking into account the uniqueness of each city. Therefore, expert consensus panels from public and private organizations should determine appropriate policies for developing utility tunnels network. This research work applies A'WOT hybrid method combining SWOT analysis and analytical hierarchy process (AHP) to study utility tunnel planning in urban areas. The hybrid method takes account of internal resources and capabilities (strengths and weakness) and external factors (opportunities and threats). SWOT analysis is a structured way to analyze these four factors, while AHP technique achieves pairwise comparisons among factors in order to prioritize them using the eigenvector method. The quantitative strategic analysis obtained from the decision support system should be used as a preliminary step in urban planning of future utility tunnel networks.

Introduction

Modern society cannot live without utilities, and their sustainable development should be incorporated as a key factor in urban underground space (UUS) planning (Cano-Hurtado and Canto-Perello, 1999). This need is part of European Union policy in order to pursue the objective of sustainable development to ensure a high level of environmental protection (Steurera and Bergerb, 2011; Martin-Utrillas et al., 2015a). Bobylev (2009) suggested that UUS should be addressed in urban planning to improve the use of city resources. By far, the most extensive use of the urban subsurface is the use of UUS for utilities as Carmody and Sterling (1993) pointed out. The growing scarcity of UUS and its rising cost are promoting the use of techniques involving joint utilization to optimize UUS consumption (Zevgolis et al., 2004; Rogers and Knight, 2014). Once an underground facility or utility is placed, the UUS can never be restored to its original condition. The UUS is a non-renewable resource and its value has been ignored for a long time (Duffaut, 1996; Duffaut and Labbe, 2002; Benardos et al., 2014; Nakou et al., 2014). Therefore, these facilities must include environmental sustainability factors in their design (Canto-Perello et al 2009; Hunt et al., 2011, Sterling et al., 2012). UUS is not sustainable without a proper infrastructure planning (Curiel-Esparza et al., 2004; Hunt and Rogers, 2005; He et al., 2012; Zhang et al., 2013). Planning for an UUS sustainable future consists of the ability to lessen the use of conventional trenching and improving joint-use of UUS for utilities.

Placement of utilities has not been usually accomplished in a sustainable way, resulting in a veritable maze of conduits and cables in UUS. Moreover, there is a growing public awareness and impatience with street trenches and their associated traffic interferences, noise pollution, dust control, lost business revenue and accidental utility cuts (Hayes et al., 2012; Matthews et al., 2015). In order to improve sustainability in the shallow underground, the use of multi-purpose utility tunnels (MUT) to integrate urban utilities has an enormous potential for our cities (Curiel-Esparza and Canto-Perello, 2012; Hunt et al., 2014; Lancellotti and Marins, 2015). These systems are capable of integrating different urban services in an easily accessible space at any point of their length (Kolonko and Madryas, 1996; Canto-Perello and Curiel-Esparza, 2001). The analysis of the existing underground facilities have indicated that MUTs are a solution that offers more advantages, even when the initial construction costs are higher in comparison with traditional techniques (Madryas, 1990; Canto-Perello and Curiel-Esparza, 2006). The use of MUTs instead of traditional trenching can be properly planned to reduce long-term maintenance efforts and traffic interferences (Yeung and Wong, 2013). However, adequate governance and security management should be an essential part of every decision undertaken in MUTs (Canto-Perello et al., 2013). In addition, the identification of hazards and control of risk are key elements of any MUT project (Canto-Perello and Curiel-Esparza, 2003; Curiel-Esparza and Canto-Perello, 2005; Li et al., 2015). Consequently, adequate MUT planning for each case is a complex and synergistic problem, as it depends on many incommensurable criteria that must be weighed to achieve a balance between technical, economical, social and environmental sustainability (Canto-Perello et al, 2015). The future city design requires a scientific way of making decisions (Saaty and Sagir, 2012). As Legrand (2004) suggested, the promotion of MUTs needs the development of multicriteria decision making methods (MCDM). MCDM allow intangibles to be assessed in order to avoid short-sighted UUS planning (Curiel-Esparza and Canto-Perello, 2013;

Martin-Utrillas et al., 2015b). SWOT technique is a effective and comprehensive study of internal and external factors, however these factors may not be easily measured. By integrating with AHP, researchers can provide a measure of quantitative importance for these SWOT factors. SWOT and AHP analysis integration to incorporate stakeholder priorities have been shown as a reliable hybrid method in decision making process (Lee and Walsh, 2011; Kajanus et al., 2012; Yavuz and Baycan, 2013; Bartusková and Kresta 2015). Combining AHP in SWOT analysis, yields analytical priorities for the factors included in SWOT analysis and makes them commensurable. In this manner the key weakness of SWOT method can be avoided. Significant quantitative information is obtained from comparisons of the SWOT factors using AHP technique. For example, whether there is a particular weakness needing most efforts, or if the utility tunnel network is expected to be faced with future threats exceeding urban underground opportunities. The purpose of this article is the development of a MCDM capable of dealing with intangibles in the early stages of MUT networks planning.

SWOT and AHP analysis methods for strategic underground planning

The key issue of the decision making and planning in MUT networks is the active participation of the public authorities and private companies whose points of view could be conflicting among them. There are general agreement that SWOTs are useful in early stages of long-term strategic planning (Helms and Nixon, 2010; Görener et al., 2012). An SWOT analysis is a flexible technique, consisting of gathering opinions from a panel of experts to evaluate internal strengths and weaknesses, as well as external opportunities and threats. Experts were asked to answer questions from a survey developed by the authors. However, SWOT technique does not analytically determine the priority of internal and external factors. Kurttila et al. (2000) found that the result of SWOT analysis is usually a superficial and imprecise listing or an incomplete qualitative study of internal and external factors. In this case, analytical hierarchy process (AHP) will be applied to enhance the SWOT examination and its results by allowing for prioritizing internal and external factors using the panel of expert judgments. The panel consists of ten experts with recognized competence and knowledge in the field of urban planning and utilities. And their work has been focused on the city of Valencia (Spain).

This research work applies A'WOT hybrid method combining SWOT analysis and AHP. This hybrid technique allows to study the external and internal factors contributing to the success of a MUT network. The AHP is capable of dealing with complex engineering projects involving technological, economical and social dimensions (Curiel-Esparza et al., 2014; Kursunoglu and Onder, 2015; Martin-Utrillas et al., 2015c). In addition, the proposed method increases a better understanding of the governance and relationships among public authorities and private companies in urban subsurface commodities (Canto-Perello and Curiel-Esparza, 2013). The internal and external factors must be carefully analyzed prior to the SWOT technique. The aim of this research is to develop a tailored A'WOT analysis to provide relevant information to both local authorities and private companies to contribute to the environmental, economic, and social sustainability of the UUS. To this end, the hybrid model will be structured in three surveys.

First survey to determine internal and external origin factors

The first step to overcome is the construction of the SWOT matrix. To this end, internal and external aspects are scrutinized by the panel of experts. The strengths and weaknesses are internal tangible or intangible attributes of the MUTs as compared to traditional trenching techniques. Strengths are positive internal factors as: increase UUS sustainability, UUS is a finite and non-renewable resource; increase reliability of underground utilities minimizing damages due to soil settlements, blind digging and top loads; reducing probability of rupture to pipe-type systems because of minimum corrosion problems which usually appear in buried pipelines; easier limited extension of utilities as compared to conventional trenching if tunnel system is properly planned; easier inspection, preventive maintenance and repair thus permitting early identification and reduction of potential failures. Whereas weaknesses are internal factors that are a disadvantage for the MUTs as: exposure to liability issues for improper or negligent installation and operation in one utility may cause damage to all in-tunnel utilities, and result in a claim for damages; more complicated installation and maintenance planning as many different utility companies are occupying the same underground facility; increase interference among utilities under some conditions like undesirable drinking water temperature rises due to insufficient insulation in central heating conduits or poor tunnel ventilation, and last, difficulty in providing utility connections between MUTs and buildings.

The opportunities and threats are external tangible or intangible factors of the MUTs as compared to traditional trenching. Opportunities are possibilities granted by the external drivers to improve the strengths and reduce the weaknesses. Opportunities are positive external factors as: prevent traffic interruption and congestion due to repeated excavation of roads, avoiding travel delays and lost business revenue; improvement of community appearances by elimination of noise and dust pollution due to street cutting and trenching; reduce street maintenance cost by lengthening road pavement life; decrease cost in maintenance of subsurface utilities; reduction of right-of-way space requirements; elimination of leaks and ruptures due to traffic and earth movement loads, and possibility of dual use as civil defense shelter. Whereas threats are external aspects that are a disadvantage for the MUT networks as: difficulty in allotting and quantifying benefits, and assessing appropriate share of costs to beneficiaries; difficulties in establishing liability in case of damage to tunnel installations or injury to third parties; MUTs and transportation networks coordination; increased criticality and security concerns, becoming an inviting target due to major outages of all systems from a single act of sabotage or vandalism as compared to separate systems; difficulties with sewerage connections and result in sanitary and storm sewers being deeper, and adding extra costs due to utility conduits and lines of some services to be longer as a result of being in-tunnel. And finally, as shown in Fig. 1, the SWOT matrix schematization is formulated based on results from the panel of experts.

Second survey to evaluate strengths, weaknesses, opportunities and threats

The second survey sent to the panel of experts will be used to assess SWOT elements, i.e. strengths, weaknesses, opportunities and threats. Afterwards, the prioritization of SWOT elements will be accomplished applying AHP technique. As shown in Table 1, the linguistic terms together with a 9-point scale are used by the panel of experts for pairwise comparison (Saaty, 2012). Taking into account Fig. 1, experts evaluate SWOT elements as illustrated in Table 2. The geometric mean method will be used as aggregation procedure to construct pairwise comparison matrix from experts' judgments (Saaty and Vargas, 2007), as follows:

$$a_{ij} = \prod_{k=1}^{10} \left(a_{ij}^{(k)}\right)^{1/10}$$

The square and reciprocal matrix from the pairwise comparisons is as follows:

$$E_{SWOT} = \begin{bmatrix} 1.0000 & 2.9279 & 0.6118 & 0.3749 \\ 0.3415 & 1.0000 & 0.3007 & 0.3165 \\ 1.6345 & 3.3254 & 1.0000 & 1.7776 \\ 2.6673 & 3.1598 & 0.5626 & 1.0000 \end{bmatrix}$$

After developing the pairwise comparison matrix for the SWOT elements (E_{SWOT}), the relative priority of each element will be determined applying the eigenvector method. The relative weight of each SWOT element is given by the principal eigenvector (ω_{SWOT}) corresponding to the largest eigenvalue (λ_{max}). To find this priority vector, the linear system $E_{SWOT} \cdot \omega_{SWOT} = \lambda \cdot \omega_{SWOT}$ must be solved applying $det(E_{SWOT} - \lambda \cdot I) = 0$. Therefore, the priority vector of the SWOT elements is as follows:

$$\omega_{SWOT} = \begin{bmatrix} 0.1980 \\ 0.0910 \\ 0.3836 \\ 0.3274 \end{bmatrix}$$

The key improvement of AHP is to analyze whether or not inconsistency occurs in the experts' surveys. Panelists are usually unable to express consistent preferences in case of several criteria and attributes. To avoid inconsistency, the AHP technique calculates the inconsistency of the pairwise comparison matrix and establish a consistency threshold which must not be exceeded. The consistency ratio (CR) is measured for ranking consistency. Maximum consistency ratio must be 5% for a 3 by 3 matrix, 9% for a 4 by 4 matrix, and 10% for a larger matrix. For higher value of CR, panelists' questionnaires needs to be re-examined. The CR is measured by dividing the consistency index (CI) by the random consistency index (RCI) obtained from Saaty (2012), as follows

$$CR = \frac{CI}{RCI}$$

The CI is determined using the matrix order (n) and the largest eigenvalue (λ_{max}) of the pairwise comparison matrix, as follows

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Thus, the results of the pairwise comparisons shown in Table 3 are quantitative values expressing the importance of the SWOT groups studied. The second step of the process followed to determine the relative preference rating of strengths, weaknesses, opportunities and threats is completed.

Third survey to measure the priority of SWOT factors

After weighting SWOT groups, the following step is to weight and rate individual SWOT factors. Tables 4 to 7 show the pairwise comparison matrix of strengths, weaknesses, opportunities and threats, respectively. The geometric mean method has been used as aggregation procedure to construct each pairwise comparison matrix from panelists' judgments. The positive internal factors (strengths) compared in pairs are: increase underground space sustainability (IUS); increase reliability of underground utilities (IRU); reducing probability of rupture to pipe-type systems (RPR); easier limited extension of utilities (ELE); and easier inspection, preventive maintenance and repair (EIM). The positive external factors (opportunities) compared in pairs are: prevent traffic interruption and congestion (PTI); improvement of community appearances (ICA); decrease cost in maintenance of subsurface utilities reduction of right-of-way space requirements (DCM); elimination of leaks and ruptures due to traffic and earth movement loads (ELR); and possibility of dual use as civil defense shelter (CDS). The internal aspects (weaknesses) that are a disadvantage for the MUT networks include: exposure to liability issues for improper or negligent installation and operation (ELN); more complicated installation and maintenance planning (CIM); increase interference among utilities (IIU); and difficulty in providing service connections (DSC). The external aspects (threats) that are a disadvantage for the MUT networks include: difficulty in allotting and quantifying benefits (DQB); difficulties in establishing liability in case of damage (DEL); MUTs and transportation networks coordination (UTC); increased criticality and security concerns (ICS); difficulties with sewerage connections (DSC); and adding extra costs due to utility conduits and lines (EXC).

As in previous sections, the eigenvector method has been applied to obtain the priority vector, and a consistency analysis is performed for each case. Eigenvalues, consistency indexes and consistency ratios for SWOT groups are shown in Tables 4 to 7. Maximum consistency ratio values are given depending on n value. In this case for n=4 consistency ratio must be below 9%, and for n=5 consistency ratio must be below 10%, hence the results are reliable. After weighting individual factors and using these weights as additional multipliers for SWOT groups, their global priorities are assessed as shown in Table 8.

Conclusions

The future of MUTs projects requires better strategies and understanding at an early stage in our UUS planning. Nowadays, engineers have been accused of being short-sighted in their approach to the city they serve. The ability to convince the public that their decisions are made for the public good in the long-term must be encouraged. This study provides a participatory, systematic and comprehensive technique to understand and analyze key drivers for UUS sustainable planning. The active participation of both public and private sectors in order to reach consensus strategies in UUS planning is unavoidable. To this end, this research work applies A'WOT hybrid method combining SWOT analysis and AHP method to promote joint-use of UUS using MUTs. Moreover, the SWOT factors studied can be tailored to the particular needs of every city. With this hybrid technique, the urban planners and municipal engineers view the problem from every angle and know all the strengths, opportunities, weaknesses and threats involved.

The SWOT factors most valued by experts have been Opportunities (38.36%) and Threats (32.74%) which are the external factors as shown in Fig. 2. The remaining 28.90% is distributed among the internal factors, i.e. Strengths (19.80%) and Weaknesses (9.10%). Results show that preventing traffic interruption and congestion (13.75%) and improvement of community appearances (13.07%) are the most relevant opportunities among the panelists to be considered in the strategic planning of UUS. While on the other hand, the results can shed light on negative factors that threaten the use of MUTs as increased criticality and security concerns (10.25%) and utility tunnels and transportation networks coordination (9.82%). In addition, the A'WOT method highlighted two primordial strengths of MUTs which are the increase of underground space sustainability (7.37%) and the easier inspection, preventive maintenance and repair of utilities (6.04%). Moreover, the panel of experts pointed out that MUTs present no new problems of an engineering, management and liability nature that could not be solved with adequate planning.

Efforts to achieve UUS sustainability must include innovation to all types of infrastructure. UUS innovation should be aimed towards meeting the future needs, and not just to minimize economical factors. Proper urban planning must promote joint-use for sustainability of the non-renewable UUS. To this end, MUTs should be considered one of the most sustainable UUS facilities. MUTs become significant not only for reducing the need to dig up streets for utilities, but also for the effective use of the valuable UUS. Establishing sustainable strategies in UUS requires appropriate decision support procedures for analyzing complex issues in which intangible criteria cannot be neglected. Promoting public and private decision support is a key factor of sustainable UUS policies. Threats and weaknesses should be minimized, while strengths and opportunities should lead to competitive advantages. The proposed A'WOT hybrid method, combining SWOT analysis and AHP method, supports quantitative strategic analysis in the early stages of urban underground planning for future utility tunnel networks.

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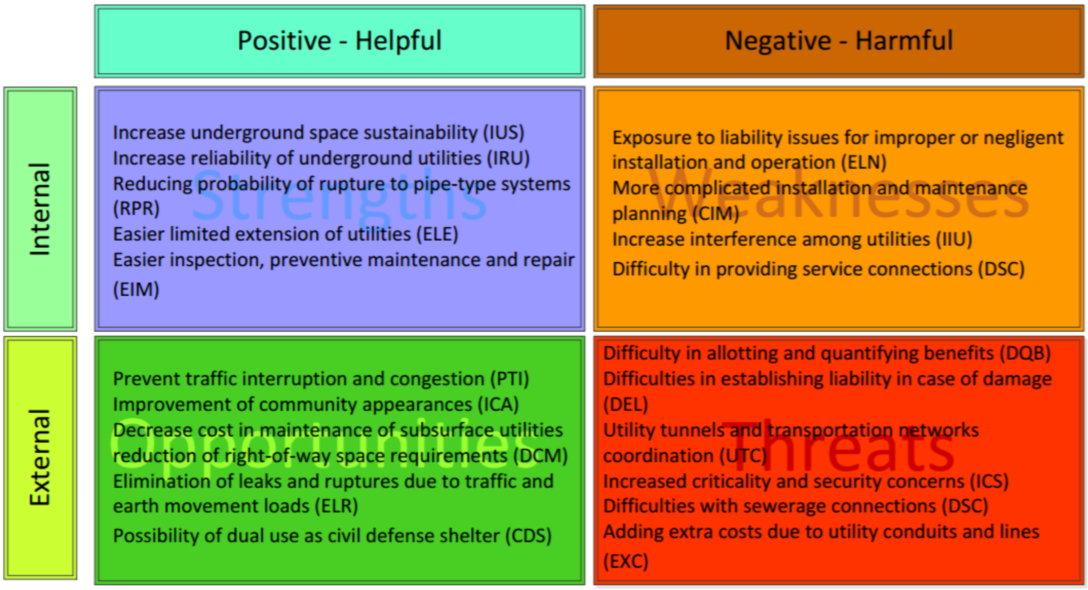

Fig. 1. SWOT matrix for strategic decision support system for MUT's planning.

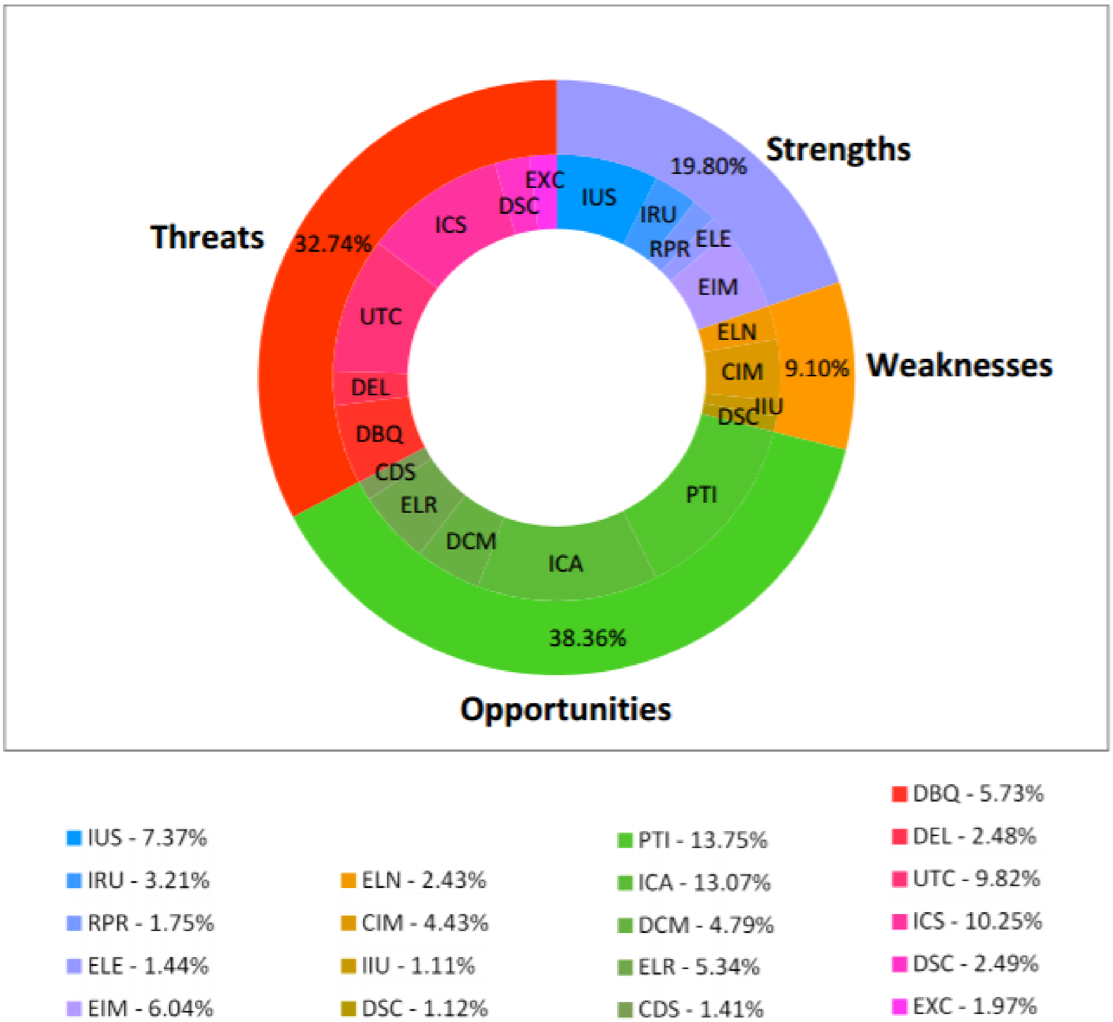

Fig. 2. A'WOT global priorities for MUT's strategic analysis in urban underground.

Table 1

Linguistic terms and its translation into numeric 9-point scale used by experts for pairwise comparison.

Linguistic term	Relative intensity	Meaning
EP	9	A SWOT element is extremely preferred to another
VP	7	A SWOT element is very strongly preferred to another
MP	5	A SWOT element is moderately preferred to another
SP	3	A SWOT element is slightly preferred to another
QP	1	A SWOT element is equally preferred to another
SN	1/3	A SWOT element is slightly non-preferred to another
MN	1/5	A SWOT element is slightly non-preferred to another
VN	1/7	A SWOT element is very strongly non-preferred to another
EN	1/9	A SWOT element is extremely non-preferred to another

Table 2

Evaluation results of the SWOT elements scrutinized by the panel of experts.

Pairwise criteria	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	Geometric mean
Strengths vs. Weaknesses	SP	QP	QP	SP	VP	MP	VP	SP	QP	VP	2.9279
Strengths vs. Opportunities	MN	MN	VN	QP	VN	SP	SP	QP	VP	VN	0.6118
Strengths vs. Threats	SN	SN	QP	QP	SN	SN	MN	SN	MN	SN	0.3749
Weaknesses vs. Opportunities	VN	EN	MN	MN	MN	QP	QP	SP	EN	VN	0.3007
Weaknesses vs. Threats	SN	MN	SN	VN	VN	MN	SN	QP	QP	SN	0.3165
Opportunities vs. Threats	VP	SP	QP	MP	SN	SN	SP	QP	SP	SP	1.7776

Table 3

Pairwise comparisons of SWOT factors.

SWOT group	Strengths	Weaknesses	Opportunities	Threats	Priority vector
Strengths	1.0000	2.9279	0.6118	0.3749	0.1980
Weaknesses	0.3415	1.0000	0.3007	0.3165	0.0910
Opportunities	1.6345	3.3254	1.0000	1.7776	0.3836
Threats	2.6673	3.1598	0.5626	1.0000	0.3274
λ_{max} = 4.1501, CI = 0.0500, CR = 0.0562 < 0.09 OK					

Table 4
Priority vector and consistency analysis of the pairwise comparison matrix of Strengths.

Strengths	IUS	IRU	RPR	ELE	EIM	Priority vector
IUS	1.0000	1.7640	4.5437	4.3934	1.8708	0.3720
IRU	0.5669	1.0000	2.3305	1.2362	0.5920	0.1621
RPR	0.2201	0.4291	1.0000	2.0880	0.2352	0.0884
ELE	0.2276	0.8089	0.4789	1.0000	0.1636	0.0726
EIM	0.5345	1.6891	4.2515	6.1135	1.0000	0.3049
λ_{max} = 5.2397, CI = 0.0599, CR = 0.0540 < 0.10 OK						

Table 5
Priority vector and consistency analysis of the pairwise comparison matrix of Weaknesses.

Weaknesses	ELN	CIM	IIU	DSC	Priority vector
ELN	1.0000	0.3845	2.5811	2.6011	0.2670
CIM	2.6011	1.0000	3.8060	2.7821	0.4872
IIU	0.3874	0.2627	1.0000	1.1847	0.1224
DSC	0.3845	0.3594	0.8441	1.0000	0.1234
λ_{max} = 4.0867, CI = 0.0289, CR = 0.0325 < 0.09 OK					

Table 6
Priority vector and consistency analysis of the pairwise comparison matrix of Opportunities.

Opportunities	PTI	ICA	DCM	ELR	CDS	Priority vector
PTI	1.0000	1.4633	2.9794	2.3126	7.8699	0.3584
ICA	0.6834	1.0000	2.7374	3.6474	8.5588	0.3408
DCM	0.3356	0.3653	1.0000	1.2045	2.8311	0.1249
ELR	0.4324	0.2742	0.8302	1.0000	6.0666	0.1391
CDS	0.1271	0.1168	0.3532	0.1648	1.0000	0.0368
λ_{max} = 5.1367, CI = 0.0342, CR = 0.0308 < 0.10 OK						

Table 7
Priority vector and consistency analysis of the pairwise comparison matrix of Threats.

Threats	DBQ	DEL	UTC	ICS	DSC	EXC	Priority vector
DBQ	1.0000	2.1974	0.4438	0.5966	2.0189	5.0325	0.1749
DEL	0.4551	1.0000	0.3270	0.2933	0.5345	1.6332	0.0758
UTC	2.2533	3.0578	1.0000	1.1161	3.1356	6.7055	0.3001
ICS	1.6761	3.4101	0.8960	1.0000	5.5198	7.4207	0.3130
DSC	0.4953	1.8708	0.3189	0.1812	1.0000	0.4874	0.0761
EXC	0.1987	0.6123	0.1491	0.1348	2.0519	1.0000	0.0602
λ_{max} = 6.3897, CI = 0.0779, CR = 0.0623 < 0.10 OK							

Table 8

Global priority scores of SWOT factors.

SWOT group	Priorities	SWOT factor	Local priority	Global priority
Strengths	0.1980	Increase underground space sustainability (IUS)	0.3720	0.0737
		Increase reliability of underground utilities (IRU)	0.1621	0.0321
		Reducing probability of rupture to pipe-type systems (RPR)	0.0884	0.0175
		Easier limited extension of utilities (ELE)	0.0726	0.0144
		Easier inspection, preventive maintenance and repair (EIM)	0.3049	0.0604
		λ_{max} = 5.2397, CI = 0.0599, CR = 0.0540 < 0.10 OK		
Weaknesses	0.0910	Exposure to liability issues for improper or negligent installation and operation (ELN)	0.2670	0.0243
		More complicated installation and maintenance planning (CIM)	0.4872	0.0443
		Increase interference among utilities (IIU)	0.1224	0.0111
		Difficulty in providing service connections (DSC)	0.1234	0.0112
		λ_{max} = 4.0867, CI = 0.0289, CR = 0.0325 < 0.09 OK		
Opportunities	0.3836	Prevent traffic interruption and congestion (PTI)	0.3584	0.1375
		Improvement of community appearances (ICA)	0.3408	0.1307
		Decrease cost in maintenance of subsurface utilities reduction of right-of-way space requirements (DCM)	0.1249	0.0479
		Elimination of leaks and ruptures due to traffic and arth movement loads (ELR)	0.1391	0.0534
		Possibility of dual use as civil defense shelter (CDS)	0.0368	0.0141
		λ_{max} = 5.1367, CI = 0.0342, CR = 0.0308 < 0.10 OK		
Threats	0.3274	Difficulty in allotting and quantifying benefits (DQB)	0.1749	0.0573
		Difficulties in establishing liability in case of damage (DEL)	0.0758	0.0248
		Utility tunnels and transportation networks coordination (UTC)	0.3001	0.0982
		Increased criticality and security concerns (ICS)	0.3130	0.1025
		Difficulties with sewerage connections (DSC)	0.0761	0.0249
		Adding extra costs due to utility conduits and lines (EXC)	0.0602	0.0197
		λ_{max} = 6.3897, CI = 0.0779, CR = 0.0623 < 0.10 OK		