Simplified Assessment of the Resilience Capacity of Urban Areas affected by Microtunneling Activities

Jorge A. Pineda, PhD[1], Sherley C. Larrañaga, PhD[2]
[1]Universidad Distrital Francisco José de Caldas & Universidad Nacional de Colombia, Sede Bogotá
japinedaj@udistrital.edu.co; jpinedaj@unal.edu.co
[2]Diceín SAS, R+D+I Department, *proyectos@diceinsas.com*

Abstract– ***Recently, in cities of developing countries, trenchless excavation technology for the underground space development projects has been incorporated in the construction stages to cause the least impact on the stability of the elements of the urban environment, favoring the mitigation of risk damage to elements already built on the surface in the intervention areas. However, some cases of irreversible and accelerated deterioration of consolidated urban areas caused by deformations induced on the surface during tunneling have shown the need to address the risk assessment that trenchless technology entails and the determination of the resilience capacity that they possess. the areas to intervene to face the risk caused and recover from the consequences. This article presents an approach to the simplified evaluation of the resilience of urban areas in the face of the execution of low coverage tunnels using trenchless technology based on multi-criteria interdisciplinary analysis associated with the definition of the aspects of robustness, redundancy, resourcefulness, and capacity of recovery implicit in the classical definition of resilience. The proposed criteria were evaluated and weighted from the assignment of values on the scale from 0 to 1, allowing a simplified quantitative evaluation of the resilience capacity at moments before and during construction for an application case in a complex intersection of the first Bogota metro line in Colombia. The proposed methodology constitutes an innovative approach as a complementary tool for risk assessment on urban environments and decision making for the sustainable implementation of trenchless technology.***

Key Words—Excavations, Microtunneling, Risk Management, Resilience, System, Urban Environment, Trenchless.

Resumen – Recientemente, en ciudades de países en desarrollo, la tecnología de excavación sin zanja para la ejecución de proyectos de aprovechamiento del espacio subterráneo ha sido incorporada en las etapas constructivas con el fin de ocasionar el menor impacto en la estabilidad de los elementos del entorno urbano, favoreciendo la mitigación del riesgo de daño de elementos ya construidos en superficie en las zonas de intervención. Sin embargo, algunos casos de deterioro irreversible y acelerado de zonas urbanas consolidadas originados por las deformaciones inducidas en superficie durante la tunelación han demostrado la necesidad de abordar la evaluación del riesgo que conlleva la tecnología sin zanja y la determinación de la capacidad de resiliencia que poseen las zonas a intervenir para afrontar el riesgo ocasionado y recuperarse de las consecuencias. Este articulo presenta un acercamiento a la evaluación simplificada de la resiliencia de áreas urbanas ante la ejecución de túneles de baja cobertura mediante tecnología trenchless a partir de un análisis interdisciplinario multicriterio asociado a la definición de los aspectos de robustez, capacidad de gestión, confiabilidad y capacidad de recuperación implícitos en la definición clásica de la resiliencia. Los criterios propuestos fueron valorados y ponderados a partir de la asignación de valores en la escala de 0 a 1, permitiendo una evaluación cuantitativa simplificada de la capacidad de resiliencia en momentos antes y durante la construcción para un caso de aplicación para una intersección compleja de la primera línea del metro de Bogotá. El enfoque metodológico propuesto constituye una aproximación innovadora como herramienta complementaria a la evaluación del riesgo sobre entornos urbanos y la toma de decisiones para la implementación sostenible de la tecnología trenchless.

Palabras Clave— Entorno Urbano, Excavaciones, Microtunelación, Resiliencia, Sistema, Tecnología Trenchless.

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I. INTRODUCTION

Worldwide, the growth of cities demands the creation of resilient infrastructure works for their sustainable development. In this scenario, the use of underground space for permanent structures imposes the need of carefully planning open deep excavations and/or tunnels by construction processes using trenchless technologies for the placement of aqueduct lines, zonal sewage collectors and subway mass transportation systems, among other applications. In urban areas, the planning and execution of deep excavations for different purposes have been recognized as some of the modern engineering problems that have the greatest impact on the physical environment in many aspects of the macro development of cities, since their implementation allows the successful materialization of high impact solutions in societies, contributing to the increase in the quality of life and well-being of people. The systems that make up deep excavations and low cover tunnels are fundamental for sustainable land use management in cities and, therefore, fundamental for the development of resilient cities.

In this context, trenchless for installation, replacement, relocation, and renovation of lifelines, such as aqueducts lines, sewage collectors, gas, electrical networks, data networks, etc., emerges as a very promising alternative in developing countries to minimize the impact on the physical environment. This construction methodology is usually more economical and helps to avoid the impact and damage risk to elements in ground surface. Among the construction methods of trenchless technology, the pipe jacking, which consists of the installation of a concrete/steel pipe by applying horizontal forces by a TBM (Tunneling Boring Machine), accompanied by a continuous process of excavation and removal of excavated material is one of the most used in Colombia, and is recognized by several authors as the one that most disturbing of the soil´s stress state, causing the highest threshold of surface displacements [1]–[3] [4][5].

Within the aspects in which a better understanding is required in projects using trenchless technology, the effects on and the capacity of urban areass to face the consequences of this kind of projects within the framework of risk management are critical aspects [1][6][7]. Some of the consequences during trenchless in the physical areas are related to the generation of surface displacements, the hazard and the probability of damage to the elements of the urban environment [2][7][8]. Especially, in Bogota, Colombia, some examples have shown dramatically the need to address these aspects in a more rational way in the planning, design, and construction stages of underground works (see figure 1, failure of the physical environment due to deformations caused by trenchless technique in a 2.0 m diameter sewage pipeline collector renovation project in the southwest of Bogota, D.C). In this case, both inadmissible surface displacements caused by trenchless micro tunneling and soil shear failures around the launching shafts were the disruptive event in the affected urban area that caused serious socio-economic and technical consequences.

A modern assessment for the evaluation of the capacity of an urban area to recover after an anthropic intervention, a micro tunneling, for example, is the evaluation of its resilience capacity within the framework of risk management in the conceptual and detailed design stages of the project. The resilience capacity is defined from equation (1), where Q(t) corresponds to a performance function that reflects the decline in the capacities of the resilient element or system for a given period, located between (t_o) (time at which the disruptive event starts) and (t_r) (time at which the disruptive event ends) [2].

$$R = \int_{t_o}^{t_r}[100 - Q(t)]dt \qquad (1)$$

The concept of resilience has gained great importance in disaster and risk management research at the international level [6], [9],[10], [11]. Although the concept of resilience is very attractive, its implementation in the planning stages of large-scale projects is still incipient in developing countries [12][13].

Fig. 1. Surface deterioration of the physical environment caused by the excavation of a tunnel with trenchless technology for the construction of an 80-inch diameter sewer in the southwest of Bogota, D.C., Colombia. Courtesy of Diceín S.A.S. (2019)

According to [14] a system that is resilient to an anthropogenic intervention can anticipate, absorb, adapt and/or recover quickly from the consequences of a potential disruptive event. Four components have been adapted to this definition of resilient systems: Robustness, Redundancy, Resourcefulness and Recovery, to determine the resilience from different fields, making this considered multidisciplinary. In urban areas affected by the development of construction works, [15] [16] determined four basic components that significantly affect the response of urban systems: deterioration of buildings, deterioration of roads, deterioration of lifelines and/or service networks and socioeconomic effects on the community.

Resilience in engineering is characterized by four properties or components, called the 4R's, previously mentioned. Robustness refers to the intrinsic capacity or resistance of the system to face a level of stress or demands without suffering loss of functionality, it can also be interpreted as the ability to maintain critical operations and functions during a crisis, it includes the concepts of resistance and structural rigidity, safety factor, probability of failure and in general the characteristics that define the compliance with design codes of the construction itself, the integral design of the structural solutions of the components. The greater the robustness of the system, the lower the probability of damage propagation and negative consequences of the disruptive event.

Redundancy refers to the ability of a system to replace its components without affecting its functionality after the disruptive event and can also refer to backup or reserve resources to support the original ones in case of specific failures. Redundancy can reduce the consequences of the event since the failure of redundant systems, or their units will not significantly affect the overall performance of the system.

Resourcefulness refers to the ability to identify problems, establish priorities and mobilize resources, as well as the capacity or ability to prepare for, respond to and manage the crisis due to the presence of a disruptive event, which includes identifying courses of action, resource planning, management of supply chains, prioritization of actions to control and mitigate damage, and effective communication of decisions. In addition, resourcefulness can contribute to measures for the development of disaster mitigation and prevention and contribute to the recovery process.

Recovery refers to the ability to address priorities over a time period to contain losses and avoid future losses, it can also be understood as the ability to rebuild and/or return to normal operations quickly and efficiently after a disruptive event, where carefully prepared contingency plans, competent emergency operations and the importance of having the right people and broad resources are determinant factors to face consequences of the disruptive event.

A conceptual interpretation of the degradation and recovery of a system's functionality is shown in Figure 2, in which the absorption of the disruptive event is reflected in the degradation of the system's functionality from time (t_d) to (t_a), the recovery efforts start immediately after the perturbation, without the system functionality changing for a period of time, from time (t_a) to time (t_r), until adequate resources are collected and strategic responses are organized, which is referred to as the assessment phase, and finally, the system functionality is expected to recover to an acceptable level of its normal operation, from time (t_r) to (t_f).

Since the performance function over time is closely linked to the deterioration of the different elements that make up the environment, in the case shown in Figure 1, both the buildings, roads and vital networks/lifelines presented a particularly serious case of loss of functionality in the time (t_d) to (t_a), due to surface displacements caused by trenchless technology. However, the period between (t_a) to (t_r) for the case in question exceeded 36 months, with enormous negative socioeconomic consequences for the project and for the community.

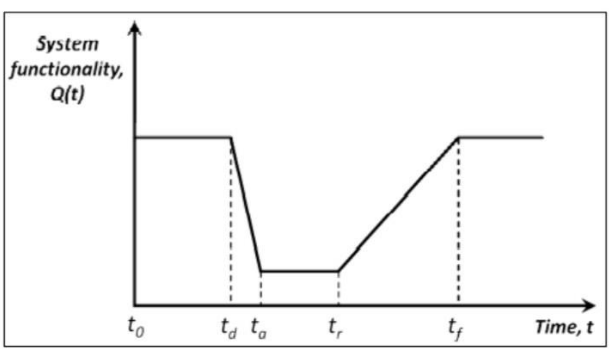


Fig. 2. Loss of performance or functionality over time of a system in engineering [2].

In systems with high robustness and redundancy, the response to a disruptive event will be higher and the loss of system functionality between (t_d) and (t_a) will be relatively small (see Figure 3).

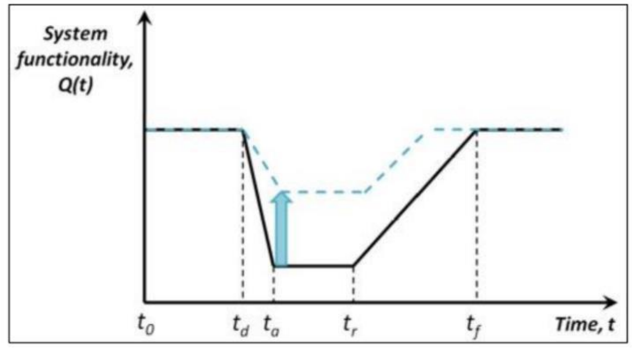


Fig. 3. Loss of performance or functionality in systems with high robustness and redundancy [2].

In systems with a high recovery capacity, the period in which the system's functionality is expected to recover to a similar functionality as before the disruptive event, the period between (t_r) and (t_f) is significantly reduced (see Figure 4).

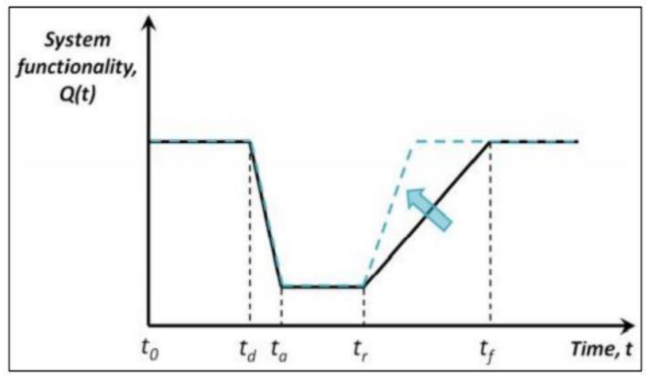


Fig. 4. Evolution of functionality or performance function in systems with high manageability and resilience [2].

Since the performance function of a system Q(t) depends on multiple factors, and the resilience ability involves the variations of this function over time, one of the main drawbacks in resilience assessment is the approach to performance functions. In order to present an innovative approach to the evaluation of the resilience capacity of an urban area subjected to micro tunneling, this article presents a first approach to the estimation of the resilience capacity of a consolidated urban area when it is subjected to construction processes using trenchless technology, pipejacking type, using a simplified methodology of weights through which it is sought to establish in two different moments, before and after the intervention. The methodology was applied to a sector of interest as a case study considered within the framework of the construction of the first metro line of Bogota.

II. METHODOLOGY FOR RESILIENCE ASSESMENT IN URBAN AREAS AFFECTED BY MICROTUNNELING

As mentioned above, the estimation of resilience capacity depends on the four components of this concept (4R´s). According to [6][7], the resilience capacity of consolidated areas in which engineering projects have been built in the face of natural hazard scenarios such as floods or earthquakes can be evaluated in an interval from 0 to 1, where 0 means that the system has no resilience, and 1 means that the system is totally resilient. For the present case, the resilience index was taken as the ratio between the resilience obtained for a time 1 or initial time, before the disruptive event, and a time 2 that represents the instant after the disruptive event, the equation presented is as follows:

$$RI = R(t_2)/R(t_1) \quad (1)$$

In eq. 1, RI represents the resilience index of the intervention zone, $R(t_2)$ is the resilience capacity for a time after the occurrence of the disruptive event, in this case, the micro tunneling with the Trenchless system, and $R(t_1)$ is the resilience before the disruptive event, moment for which the performance function is associated to the normal operation of the system components. For the estimation of the resilience index and the components of $R(t_1)$ and $R(t_2)$, it is proposed that the index varies between 0 and 1, like its components. In addition, for the general evaluation of each criterion, a weighting ranging from 0 to 100% was proposed, the higher the weighting, the greater the importance or relevance of the evaluated aspect. (IR) therefore represents the cumulative loss of system functionality expected during the estimated downtime, which is key for stakeholders and decision makers of a system, understood as the set of urban elements that are in operation before a micro tunneling process [17], [18]. (t_1) will be any time between (t_d) and (t_a) and (t_2) will be any time between (t_r) and (t_f) from Figures 2 to 4.

Since the main effect of microtunneling by means of pipe-jacking consists of the appearance of surface displacements or subsidence due to the use of trenchless technology, there is a clear correlation with surface damage to hydraulic pipelines, civil structures and urban road infrastructure and their deterioration, which ultimately affects the physical environment. For each of these elements, the definitions of the factors that together define robustness, redundancy, resourcefulness, and recovery will be presented. Equations 2 and 3 present the proposal for estimating $R(t_1)$ and $R(t_2)$:

$$R(t_1) = 0.40ROB_1+0.40RED_1+0.10RES_1+0.10RCV_1 \quad (2)$$

$$R(t_2) = 0.20ROB_2+0.20RED_2+0.30RES_2+0.30RCV_2 \quad (3)$$

In time (t_1), resilience is defined by the performance status of the system, so a percentage of 40% was assigned for robustness and 40% for redundancy, taking into account that these are the components that largely define the resilience capacity of the elements of the urban area; these percentages are based on the analysis performed by the authors [15], [19], [20] and on the response conditions of infrastructure elements according to practices in Colombia [1], [7]. For resourcefulness and recovery capacity, a weighting of 10% was assigned to each based on the importance of these aspects when the system is under normal performance conditions, with the activation of protocols for emergency attention and risk management in the project development area.

In time (t_2), resourcefulness and recovery capacity take on greater importance after the occurrence of the disruptive event that affects the elements of the urban area; therefore, a greater weighting has been assigned to these factors, which add up to 60% of the resilience capacity, while robustness and redundancy collaboratively reach 40%, considering that the recovery of the affected systems will be carried out in compliance with the technical regulations at that time.

Next, we will present the particularities of the variables that define resilience in this proposal, both in (t_1) and (t_2), considering the context of the development of activities for the transfer of aqueduct and collector sewage networks, using trenchless technology, in a sector of the project for the first line of the Bogotá subway.

A. *Robustness*

The main factors considered for the evaluation of the robustness of the urban area are based on the response of buildings, roads, and networks/lifelines from numerical simulations, complemented with field visits and secondary information. The general robustness equation is presented in equation 4, which includes 4 aspects that define the susceptibility to damage of the elements of the system exposed to deflections caused by surface microtunnelling. The equation presents weighting values whose sum is 1 (100%) assigned from [2], [3], [4]. The highest weighting has been given to the vulnerability of buildings in an area of influence of 100m around, since these structures safeguard human life, and their deterioration implies considerable social and economic losses.

$$ROB(t_1) = ROB(t_2) = 0.4(R1)+0.3(R2)+0.15(R3)+0.15(R4) \quad (4)$$

(R1) represents the fragility of the type of construction of buildings in the vicinity of the area affected by microtunnelling based on criteria associated with the type of construction, its materials and the presence of structural systems capable of dissipating energy in earthquakes and which, in the case of unforeseen settlements, will respond to the stress, on a scale between 0 and 1 (see Table 1); (R2) is the maximum deflection expected at the surface from numerical simulations normalized by the maximum displacement tolerable by the structure according to the criterion proposed by [5], [18], [21], [7] (see table 2), (R3) corresponds to the deflections of the pipes that make up vital networks normalized by the maximum allowable deflection according to the pipe material for diameters greater than 10 inches (see table 3) and (R4) corresponds to the maximum deflection at the surface of the roads near the intervention zone obtained from numerical simulations and normalized by the maximum allowable deflection according to the technical deterioration criteria for subsidence that indicate compromise of the body layers of pavement structures by settlement defined in [22],[23],[24].

TABLE I
VARIABLES DEFINING ROBUSTNESS: (R1) FRAGILITY OF BUILDINGS IN THE EVENT OF SETTLEMENT

Variable	Weighing
Simple buildings (F) and light structures (E), with several floors greater than or equal to 2	0.10
Structures with poor containment (D), with a few floors greater than or equal to 4	0.10
Structures with poor confinement (D), with number of floors between 2 and 3.	0.40
Reinforced Masonry (C), Reinforced Buildings (B) and Buildings with special reinforcement (A) regardless of the number of floors.	0.95

TABLE II
VARIABLES THAT DEFINE ROBUSTNESS: (R2) SURFACE DEFLECTIONS IN BUILDINGS NORMALIZED BY THE MAXIMUM TOLERABLE DISPLACEMENT

Variable	Weighing
$(\delta_m/\delta_t)^a$ <0.2	1.0
0.2 < $(\delta_m/\delta_t)^a$ < 0.4	0.8
0.4 < $(\delta_m/\delta_t)^a$ < 0.6	0.6
0.6 < $(\delta_m/\delta_t)^a$ < 0.8	0.4
0.8 < $(\delta_m/\delta_t)^a$ < 1.0	0.2
1.0 < $(\delta_m/\delta_t)^a$ < 1.2	0.1
$(\delta_m/\delta_t)^a$ > 0.2	0

[a] (δ_m/δ_t): Maximum displacement caused by microtunneling normalized by the maximum tolerable displacement according to the type of building, in this case, L/300, where L is the estimated length between support points of columns around influence of the intervention site.

TABLE III
VARIABLES THAT DEFINE ROBUSTNESS: (R3) DEFLECTIONS IN SERVICE PIPELINES NORMALIZED BY THE MAXIMUM TOLERABLE DISPLACEMENTS

Variable	Weighing
$(\delta_{mr}/\delta_{tr})^a$ <0.2	1.0
0.2 < $(\delta_{mr}/\delta_{tr})^a$ < 0.5	0.7
0.5 < $(\delta_{mr}/\delta_{tr})^a$ < 0.8	0.5
0.8 < $(\delta_{mr}/\delta_{tr})^a$ < 1.0	0.2
$(\delta_{mr}/\delta_{tr})^a$ > 1	0

[a] $(\delta_{mr}/\delta_{tr})$: Maximum displacement caused by microtunneling in pipes of service networks such as aqueduct and sewage in the area, normalized by the maximum tolerable displacement according to the type of pipe.

TABLE IV.
VARIABLES THAT DEFINE ROBUSTNESS: (R4) DEFLECTIONS IN PAVEMENTS NORMALIZED BY THE MAXIMUM TOLERABLE DISPLACEMENT OF THE PIPE

Variable	Weighing
$(\delta_{mp}/\delta_{tp})^a$ <0.2	1.0
0.2 < $(\delta_{mp}/\delta_{tp})^a$ < 0.6	0.7
0.6 < $(\delta_{mp}/\delta_{tp})^a$ < 1.0	0.3
$(\delta_{mp}/\delta_{tp})^a$ > 1	0

[a] $(\delta_{mp}/\delta_{tp})$: Maximum displacement caused by microtunneling flexible pavement structures, normalized by the maximum tolerable displacement for a multilayer system: 20mm for rutting generation.

B. *Redundancy*

As already mentioned, redundancy is the property of the system to continue functioning despite the effects that the system may present in the event of a disruptive event. In this case, the occurrence of vertical displacements caused by micro tunnelling can lead to deterioration of roads and buildings, so it is advisable to check whether each of the components of the affected area of influence has an alternative to continue functioning. In the case of roads, it is evaluated whether there are alternative routes to direct the traffic that at time (t_1) is accommodated in the roads of the area (RED1) (see table 5) and in the case of buildings, it is evaluated whether there are one or more buildings that correspond to any of the groups of importance defined by the seismic-resistant regulations for the site of interest (RED2) (in the Colombian case, NSR-10 [25], Title A; see table 6) that can provide the same service that they provide in (t_1). Equation 5 presents the redundancy criterion proposed mainly for the characterization of the system response before and after the occurrence of the disruptive event.

$$RED(t_1) = RED(t_2) = 0.4(RED1) + 0.6(RED2) \quad (5)$$

TABLE V
VARIABLES DEFINING REDUNDANCY: EXISTENCE OF ALTERNATIVE ROADS ROUTES IN THE AREA

Variable	Weighing
The area has alternate lanes in both directions of traffic and enough lanes so that the same traffic flow can be enough lanes to ensure the same traffic flow and to allow for traffic diversion in the event of a road closure traffic diversion in the event of road closure.	1.0
The area has alternate routes in the directions of traffic and number of lanes that can supply 70% or more of the number of lanes that can supply 70% or more of the traffic flow without causing major traffic congestion or slow traffic flow without causing major bottlenecks or slow traffic flow on the alternative the detour in the event of a road closure.	0.8
The area has alternate routes in the directions of traffic and number of lanes that can supply 70% or more of the number of lanes that can supply between 50 and 70% of the traffic flow. traffic flow on the alternate routes where the detour will be made in the event of a road closure. the detour in case of road closure.	0.5
The area has alternate roads in the directions of traffic and number of lanes that can supply 70% or more of the number of lanes that can supply between 30 and	0.20

50% of the traffic flow. traffic flow on the alternate routes where the detour will be made in the event of a road closure. the detour in case of road closure.	
Alternate roads are insufficient to meet the traffic flow, with a percentage of less than 30%. less than 30%, traffic cannot be diverted in the event of road closures. closure of the road.	0

TABLE VI
VARIABLE DEFINING REDUNDANCY: EXISTENCE OF BUILDINGS OF THE SAME USE AND IMPORTANCE IN THE INFLUENCE ZONE

Variable	Weighing
If in 100% of the affected area there are more than 10 buildings corresponding to the same group of correspond to the same group of use and Importance (according to NSR-10. A Title)	1.0
If in 100% of the affected area there are less than 10 buildings corresponding to the same group of use and Importance (according to NSR-10. A Title).	0

C. Resourcefulness

The occurrence of a disruptive event such as surface displacements may affect the economic activities carried out around influence zone and pose a risk to the population and other elements that make up the physical environment of the area. In this item, an evaluation is made of the predominant economic activities in the zone of interest affected by the disruptive event. This criterion considers aspects related to economic activities and their affectation (RS1) (see table 7), and the existence of state disaster risk management policies and the operationalization of associated actions (RS2) (see table 8). These aspects make it possible to establish whether the zone located in a city has sufficient capacity to manage the consequences of a disruptive event in the area of influence analyzed, especially the attention to the directly affected population. Equation 6 presents the proposed evaluation of resourcefulness.

$$RES(t_1) = RES(t_2) = 0.3(RS1) + 0.7(RS2) \quad (6)$$

The highest weighting has been assigned to the criterion related to the second factor mentioned, which is particular to each geographic scenario and each case [2].

TABLE VII
VARIABLES DEFINING RESOURCEFULNESS: (RES1) IMPACTS ON ECONOMIC ACTIVITIES IN THE AREA.

Variable	Weighing
Economic activities of production and primary supply, indispensable or basic activities that are indispensable or of primary necessity.	1.0
Industrial activities, production and/or distribution of merchandise, production and/or distribution of basic products and services are developed.	0.8
Industrial activities, production and/or distribution of merchandise, production and/or distribution of products and services that are not necessities.	0.4
Economic activities that are not indispensable are developed	0

TABLE VIII
VARIABLES DEFINING RESOURCEFULNESS:(RES 2)
AFFECTATIONS TO ECONOMIC ACTIVITIES IN THE INFLUENCE AREA

Variable	Weighing
Public risk management policies include the attention of different events or emergencies that may occur and have specific protocols for the attention of emergencies associated with the disruptive event.	1.0
Las políticas públicas de la gestión del riesgo comprenden la atención de diferentes eventos o emergencias que se puedan presentar, pero no poseen un amplio rango de eventos que puedan atender.	0.5
There are no risk management and disaster mitigation policies.	0

D. Recovery

Resilience is related to the ability to address priorities and achieve success in a period to contain losses and avoid future losses, it can also be understood as the ability to rebuild and/or return to normal operations quickly and efficiently after a disruptive event, where carefully prepared contingency plans, competent emergency operations and the importance of having the right personnel and resources in the right places are involved. For the evaluation of this concept, the same criteria evaluated in resourcefulness are taken into account, mainly from the socioeconomic point of view, assuming that the elements of the physical environment can be recovered but giving it a different weighting according to equation 8, considering that the most important component for inter-institutional articulation and disaster management is precisely the risk management policy framework.

$$RCV(t_1) = RCV(t_2) = 0.1(RS1) + 0.9(RS2) \quad (8)$$

The weighting criteria used for the components describing resilience range from 0 to 1, and weight the relative contributions of each factor to the system's performance function. Likewise, the assignment of the weighting factors corresponds primarily to an interdisciplinary multivariate criterion based on a combined analysis of expert judgment [1], [7]which considers the collection of quantitative and semi-quantitative technical information from case studies of open pit excavations [7], [8], [26]. The weighting factors can be easily adjusted to the conditions at each site and can be re-evaluated in future risk management scenarios.

III. CASE STUDY: RESILIENCE ASSESSMENT FOR LIFELINES TRANSFER VIA TRENCHLESS IN BOGOTA (COLOMBIA) FIRST METRO LINE

The first metro line of Bogota system will extend from the southwest of the city to "Calle 72", located in the northeast with a length of 23.9 km. The entire system will be elevated. As part of the preconstruction process, the relocation of water and sewerage networks at several road intersections along the route of the line is planned, using trenchless technology, particularly pipe-jacking. The diameters of the pipes to be relocated range from 10 to 60 inches. To demonstrate the applicability of the proposed methodology for the estimation of the resilience capacity of the physical environment, an intersection located at 68th Avenue x 22nd Street South (May 1st Avenue) has been selected. The intersection is characterized by the relocation of 40-inch diameter rainwater collection pipes at variable depths between 5m and 6m below the surface, generating what is known as low cover tunnels with variable lengths between 100m and 500m. Figure 5 shows the location of the intersection.

The geotechnical properties of the subsoil materials are presented in Table 10, which were obtained from the technical documents of the project and the compilation of technical reports from neighboring areas. The construction process related to the construction of the 4m diameter launching wells under Av. 68 and the micro tunneling of the collector was simulated in a coupled manner by means of a finite element program using the elastic properties of the soils and the Möhr-Coulomb failure criterion in the materials that make up the soil, in order to predict the surface deformations that would cause the disruptive event of the system. The analysis of the elements of the physical environment and their response were analyzed in an area of influence located 100m around the intervention site, as shown in Figure 5. Among the elements analyzed, buildings of varying heights between 2 and 4 stories were identified, most of them built before 1984, main roads consisting of flexible pavements and potable water networks of varying diameters between 2 inches and 10 inches working under pressure. Figure 6 shows an aspect of the physical environment and buildings in the vicinity of the intervention site.

Fig. 5. Study area at the intersection of Av 68 x Av 1 Mayo, Bogotá D.C., Colombia.

Fig. 6. Appearance of some buildings in the study area at the intersection of Av 68 x Av 1 Mayo, Bogotá D.C., Colombia.

The thickness of the pavement layers of the main roads was estimated at an average of 1.0 m from georadar readings made in the subway studies, while for the secondary roads the average thickness is 0.50 m. Traffic on the main roads was estimated to be greater than 8.0×10^6 axles equivalent to 8.2T, and on secondary roads the value was estimated at 15% of this value based on traffic estimates from the Metro project.

TABLE IX
GEOMECHANICAL PARAMETERS FOR NUMERICAL MODELING

Depth	Soil(*)	Total Unit Weight	Strength Parameters (Su, φ´, c´)	Stiffness Parameters (E, ν)
0.0m-2.0m	SC	17.7 kN/m3	N/A, 26°, 10 kPa	20MPa, 0.3
2.0m-5.0m	CH	17.0 kN/m3	35kPa, 25°, 10kPa	10MPa, 0.5
5.0m-10.0m	MH	16.7 kN/m3	25kPa, 21°, 8kPa	15MPa, 0.4
10.0m-15.0m	SC/SM	19.1 kN/m3	N/A, 30°, 0	30MPa, 0.3

N/A: Not applies

Regarding the buildings, most of them were self-built by the inhabitants of the area in the 1970s and 1980s. It was determined that these houses were built typically with a beam-column system with solid slabs, where the dimensions of the elements are generally as follows: columns of 40*40 cm, beams of the same dimensions, and solid slabs of approximately 12 cm. Most of these buildings do not comply with the seismic-resistant regulations in force in Colombia. Figures 7 and 8 present the results of the numerical simulations of the analyzed intersection for the trenchless technology, including a surface overload of 10 KPa (1.0 tf/m^2), corresponding to that expected during construction.

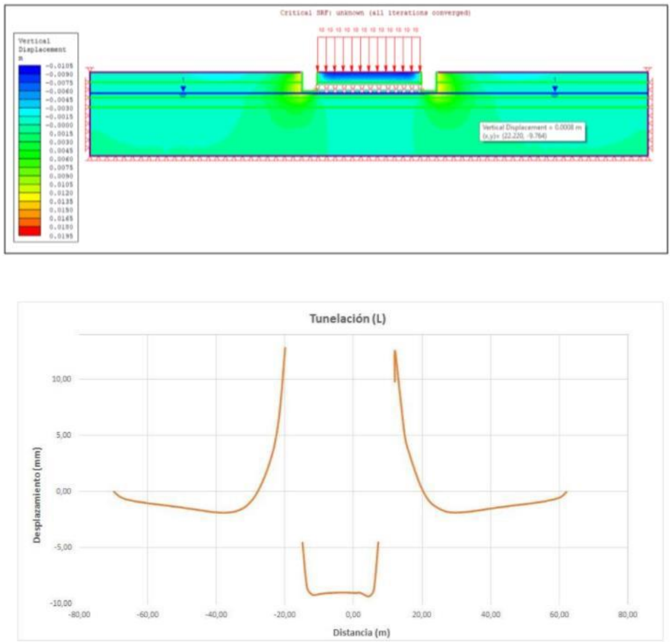
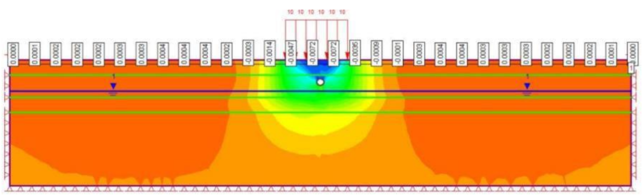


Fig. 7. Displacements from numerical simulation - Longitudinal axis trenchless system.



The evaluation of each of the aspects associated with the resilience of the system for (t_1) and (t_2), according to the proposed criteria, is presented below.

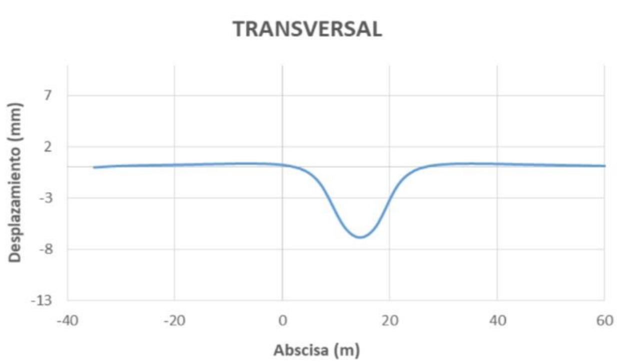


Fig. 8. Displacements from numerical simulation - Transverse axis trenchless system.

A. *Robustness*

Based on the results of the numerical simulations, the predicted vertical deformation in longitudinal and transverse directions for the pavement structures and for the buildings was analyzed and compared with the maximum allowable deformation thresholds associated with the current regulations as presented in Chapter 2. For the case of time (t_1), the tolerable threshold settlement is defined as 40 mm, according to the maximum deformation due to subsidence of a pavement structure in its service conditions, while for the time instant (t_2), once the disruptive event has occurred, predicted displacements of up to 10 mm are found, well below the threshold. For buildings, it was found from official maps of the city that around influence of the project there is a predominance of lots with dimensions of 6mx12m, taking into account this information and reasonably if the buildings in the area have at least beams and columns in two directions, according to the observations made during the field visits. These buildings, mainly for housing, can be classified as buildings with walls and nonstructural elements susceptible to damages with minor settlements according to the Colombian seismic-resistant standard (NSR-10), the vertical displacement threshold for these will be equal to 3m/1000; assuming a typical column span spacing value of 3m according to surveys conducted in the sector, therefore, the settlement limit in the damage threshold is equal to 3mm. Considering the largest vertical displacement obtained in the simulations, especially associated to the areas surrounding the trenchless system launching wells, which up to 12mm, we have values four times higher than the defined threshold. From this information, (R1) and (R2) took the values of 0.40 and 0.6, respectively.

In the pipes for networks in stoneware, concrete or asbestos-cement that correspond to some aqueduct and sewerage networks in the area, the deflection threshold for the service limit state is 1% of its diameter, considering the maximum allowable deflections in ideal conditions. For flexible pipe networks, the maximum deflection threshold is 7.5% of the pipe diameter. The determination of (R3) was made for the existing lines in the area; for (t_1), a weighting of 1 was assigned and for (t_2) the most critical scenario was taken, which corresponds to a weighting of 0 because the sewerage networks present in the area are of rigid material, considering the displacements obtained from the simulation, it is possible to affirm that microtunneling as a disruptive event, imposes deformations that exceed the permissible deflection threshold in most of the networks present. For the pavement of the roads present in the zone of influence, (R4) took the value of 0.7 according to the simulation results in both (t_1) and (t_2).

B. *Redundancy*

For the case of study, it was found that according to the traffic management plan of the Metro project, there are alternate roads capable of evacuating the projected traffic during the execution of the transfer of networks by trenchless in (t_1) and in (t_2), therefore, (RED1) takes the value of 0.5 and regarding the identification of redundancy in the use of buildings (RED2), it was found that there are residential buildings that would not be affected in (t_2) after the disruptive event with a coefficient of importance 1 and 1.2, according to the Colombian seismic resistant standard, therefore, this factor takes the value of 1.0.

C. Resourcefulness

For the evaluation of this parameter in the case study, the documents of the Secretariat of Planning of Bogota (SPB) were consulted for the localities involved in the study area. In the area, most of the economic activities that could be interrupted by the disruptive event are microenterprise activities, with companies dedicated to commerce with 42%, industry with 26%, transportation, storage, and communications with 8%, real estate and rental services with 6%, and restaurants and hotels with the same percentage. However, in the area of interest defined for the analysis, there are only buildings mainly for housing and a very low percentage of commerce, which is why (RS1) takes the value of 0.4. For (RS2), with respect to the city's risk management policies, according to those consulted within the framework of the District Strategy for emergency response, it is observed that the city of Bogotá has a structured emergency response management system that, depending on the type of emergency to be dealt with, has its own protocol for execution, attention and response, and there is also coordination between the different public and private entities in charge of dealing with emergencies, which are also empowered and qualified to respond to emergency attention in a timely manner. In previous cases of emergencies associated with excavations in Bogota (for example, failure of Cra 11 x Calle 98 in 2011), it has been possible to establish that there is an adequate response capacity of the official entities of the city, therefore, (RS2) takes the value of 1.0 for both (t_1) and (t_2).

D. Recovery

The factors mentioned in Chapter 2 of this article were considered for the estimation of resilience, most of them related to the risk management policies in place in the city of Bogotá for disaster response. With respect to risk management policies, it was established, as mentioned in the previous section, that the city of Bogotá has adequate management for emergency response, among the best in the country. Therefore, the values of (RS1) and (RS2) are the same as those defined for resilience.

E. Resilience Index

From equations 1, 2 and 3, the resilience capacity for (t_1) and (t_2) of the area affected by the trenchless intervention, and the Resilience Index (RI) were determined from the proposed approximation. The (RI) amounts to 0.95 for $R(t_1)$ values of 0.75 and $R(t_2)$ 0.71.

The resilience values for both times are relatively congruent and above the mean, according to the numerical simulations performed, it is possible to show that although the settlements are in the order of millimeters, the current conditions of the pavement, service networks/lifelines and buildings, together with the socioeconomic conditions of the area, make the urban area relatively fragile and vulnerable to the occurrence of surface displacements that can evidently become inadmissible. Considering the results obtained for the resilience index for the analyzed intersection, the value amounts to a number close to 1, this indicates that the occurrence of the disruptive event implies a slight loss of functionality of the urban urban area within the area of influence. The resilience capacity associated with the IR can be considered as adequate for the implementation of trenchless technology; however, it is necessary to deepen in other cases to validate the orders of magnitude determined in this work and its applicability in planning stages for the implementation of this technology.

IV. CONCLUSIONS

This paper has presented a proposal for the simplified assessment of the resilience index of an urban area subjected to trenchless technology. Although the resilience index is related to the resilience capacity in different scenarios for two different moments, it is not affected by the fact that this characteristic, in each of the evaluated times, is high or low, since it is mainly evaluated as the percentage variation of resilience of time 2 with respect to time 1. It was evidenced that resilience before the disruptive event (which depends largely on robustness and redundancy) is affected by the aspects of structural configuration, materials present in the system elements, soil characteristics in the area, among others; these characteristics determine the state of the urban area before the disruptive event. The analysis of more information is required to evaluate the applicability of the method presented, it reliability and the assignment of the proposed weightings for each factor that defines 4R´s and therefore resilience.

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