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Chapter

Elucidation of Seismic Soil Liquefaction Significant Factors

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Abstract

The paper develops a framework to analyze the interactions among seismic soil liquefaction significant factors using the interpretive structural model (ISM) approach based on cone penetration test. To identify the contextual relationships among the significant factors, systematic literature review approach was used bearing in mind the selection principle. Since multiple factors influence seismic soil liquefaction, determining all factors in soil liquefaction would be extremely difficult, as even a few seismic soil liquefaction factors are not easy to deal with. This study highlighted two main characteristics of seismic soil liquefaction factors. First, the seismic soil liquefaction factors–peak ground acceleration F_2 ($a_{\max}$), equivalent clean sand penetration resistance F_5 (q_{c1Ncs}), and thickness of soil layer F_{11} (T_s) influenced soil liquefaction directly and were located at level 2 (top level) in the ISM model, meaning they require additional seismic soil liquefaction factors except thickness of soil layer F_{11} (T_s) to collaboratively impact on soil liquefaction potential. The multilevel hierarchy reveals that depth of soil deposit F_{10} (D_s) is formed the base of ISM hierarchy. Secondly, Matrice d'impacts croisés multiplication appliqués à un classement (MICMAC) analysis has been employed for evaluating these identified factors in accordance with driving power and dependence power. Factors with a higher driving power should be given special consideration. Autonomous soil liquefaction factors have no reliance on other soil liquefaction factors and interfere less. In order to identify the significant factors that affect seismic soil liquefaction susceptibility, the model built in this study clearly illustrates the complex relationships between factors and demonstrates the direct and indirect relationships.

Keywords: Soil liquefaction, Interpretive structural modeling, MICMAC, Cone penetration test

1. Introduction

Seismic soil liquefaction is one of the most complicated geotechnical earthquake engineering problems due to the variability and complexity of site conditions, soil parameters and seismic parameters. All those parameters having a number of factors that cause liquefaction, all of which are of varying importance. Estimating accurate and effective soil liquefaction risks, required identification and benchmarking of the most influential factors that control soil liquefaction need to be comprehensively examined. Limited research has been conducted in the past to identify important parameters of soil liquefaction. Dalvi et al. [1] used the Analytic Hierarchy Process and entropy methods to identify important parameters among 16 factors of soil liquefaction. Zhu [2] analyzed fifteen influencing factors of soil liquefaction by mathematical statistics method. Tang et al. [3] and Ahmad et al. [4] identified significant soil liquefaction factors by employing bibliometric and systematic literature review techniques based on standard penetration test respectively through interpretive structural modeling (ISM) approach. Most of these studies considered the quantification rather than the qualitative information of soil liquefaction factors from scientific publications.

Seismic parameter, soil parameter and site conditions contain variety of factors that trigger liquefaction and discussed in detail in Section 3. As literature review search is the first step in the ISM technique to identify the important factors and their underlying relationships. Therefore, a systematic literature review (SLR) approach is used for this purpose which is described by Okoli and Schabram [5] and Tranfield et al. [6] is used. Warfield developed the ISM method between 1971 and 1974 [7], and it is based on the pair-wise comparison theory. ISM has seen some progress in terms of applications and techniques over the years [8]. Michel Godet and François Bourse introduced the Matrice d'impacts croisés multiplication appliqués à un classement (MICMAC) method. The creation of a graph that classifies factors based on driving power and dependency power is called MICMAC.

In this chapter, ISM and MICMAC methodologies are used to establish and analyze the structural hierarchical relationship and to examine the strength of the relationship between seismic soil liquefaction significant factors based on their driving power and dependence power.

2. Methodology

2.1 Interpretive structural modeling: a qualitative technique

ISM methodology, as interpretive in judgment, can be used as a systematic means of recognizing the contextual relationships between the elements associated with an issue to be examined [9]. The ISM approach has been effectively utilized in diversified set of problems, for instance, risk management in supply chains [10] and energy conversation [11]. ISM can be illustrated in the following steps for the present study, as suggested by Sushil [8]:

Step 1: Identification of factors related to the problem or issue through literature review etc.

Step 2: Using domain information, fix contextual relationships between defined factors (e.g. V–row factor influences the column factor; A–column factor influences the row factor; O–no relationship between the row and column factors; or X–both direction relations from row to column and column to row factors).

Step 3: Construct a structural self-interaction matrix (SSIM) based on pair-wise comparison between factors of system which denotes direct relationship between two factors.

Step 4: SSIM is converted to initial reachability matrix, by replacing 1 or 0 for the original symbols–V, A, X and O as per the rules for transformation (see **Table 1**).

Step 5: The transitivity of initial reachability matrix is checked in order to develop the final reachability matrix. The transitive relationships mean that if variable "x" is associated with variable "y" and variable "y" is associated with variable "z", then variable "x" is certainly associated to variable "z".

If the (*i*, *j*) entry in the SSIM is	Entry in the initial reachability matrix	
	(*i*, *j*)	(*j*, *i*)
V	1	0
A	0	1
X	1	1
O	0	0

Table 1.
Rules for transformation.

Step 6: The reachability and antecedent sets of factors are developed from the final reachability matrix. The reachability set for a particular factor includes the factor itself and other factors which it may help to achieve, and antecedent set includes factor itself and other factors that can help in achieving it. Subsequently, the intersection of these sets is found for the entire factors. The factor for which reachability and intersection sets are identical is listed in the first level. This factor is then separated from other factors for the next iteration process. Repeat the same level of iteration process until all levels of each factor are established.

Step 7: Remove the transitivity links and draw a directed graph (digraph) from the final reachability matrix.

Step 8: Convert the digraph into an ISM-based hierarchical model by replacing the nodes with statements.

Step 9: The conceptual discrepancy of model is verified and improved for necessary modifications and corrections.

2.2 MICMAC analysis

The creation of a graph that classifies factors based on driving and dependency power is a part of the MICMAC study. To arrive at the study's findings and conclusions, MICMAC analysis is used to identify the factors and validate the interpretive structural model factors.

Factors are divided into four clusters based on their driving power and dependency power in MICMAC analysis. The clusters are: Cluster I: Autonomous factors —those that are relatively cut off from the rest of the system and have little or no dependency on others; Cluster II: Dependent factors—cluster II factors are primarily dependent of other factors; Cluster III: Linkage factors—the connecting factors that are unstable and have strong driving power and strong dependence power; and Cluster IV: Independent factors—these factors have weak influence from others factors and have to be paid maximum attention owing to the strong driving power.

3. Application to the case of illustration

3.1 Interpretive structural model of seismic soil liquefaction significant factors

In the ISM technique, a first endeavor is made to ascertain the significant seismic of soil liquefaction factors from the literature using systematic literature review (SLR) approach which is recommended by Okoli and Schabram [5]. The SLR is a systematic, explicit, and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work published by researchers, scholars, and practitioners [12].

There are three groups of parameters that govern the soil liquefaction phenomenon, according to published research papers, namely seismic parameters, site conditions, and soil parameters [13–18]. Each of these contains a wide range of factors that characterize liquefaction, to a varying degree of significance. The details of these parameters are given below.

3.1.1 Seismic parameter

The vulnerability of any cohesionless soil to liquefaction during an earthquake depends on the magnitude and number of cycles of stresses or strains caused by the seismic excitation. These in turn are correlated to the intensity, duration of ground shaking and predominant frequency. The degree of soil liquefaction varies with the different earthquake magnitude. Based on on-site observations and a simple parametric study, Green and Bommer [19] have concluded that a small earthquake with a moment magnitude of 4.5 will trigger liquefaction in highly susceptible soil deposits. However, for soil profiles suitable for building structures, the minimum earthquake magnitude is about 5 that cause liquefaction. Tesfamariam and Liu [20] considered the Stark and Olson [21] earthquake liquefaction datasets and intuited that with increase in M and $a_{\max}$, the likelihood of liquefaction increases. Peak ground acceleration (PGA) is a function of earthquake magnitude, site to fault distance, fault type and soil type as per Boore et al. [22] and usually used to quantify the ground motion intensity.

Pirhadi et al. [14] used closest distance to rupture surface which is among the other seismic parameters such as earthquake magnitude and peak ground acceleration as an influence factor and concluded that among the seismic parameters earthquake magnitude, peak ground acceleration and closest distance to rupture surface illustrate lesser effects on liquefaction triggering as compared to the cumulative absolute velocity. It is generally agreed, that earthquake magnitude, peak ground acceleration, and closest distance to rupture surface are the three major factors that affect the seismic intensity at the site.

3.1.2 Soil parameter

Liquefaction is usually observed in shallow, loose, saturated cohesionless soils subjected to strong ground motions. In case of in-situ cone penetration test, soil behavior type index is used to classify soils based on fines content presented by Robertson and Wride [23]. The liquefaction susceptibility depends on soil type, where fine-size particles are easier to liquefaction than coarse particles.

The type of soil that is more prone to liquefaction is one in which deformation resistance is mobilized by particle friction. When other factors like grain shape, uniformity coefficient, and relative density are held constant, the frictional resistance of cohesion less soils decreases as grain size decreases. Gravelly soils mobilize more strength during shearing and dissipate excess pore pressures more quickly than sandy soils. There are some case histories [24–26] that show liquefaction in loose gravelly soils during severe ground shaking or when the gravel layer is confined by an impervious layer.

The strength of soil liquefaction may vary depending on the fines content. Several studies have found that fines content has a significant impact on soil susceptibility to liquefaction [24–26]. Soil liquefaction potential increases as fines content exceeds 30%. When fines content exceeds 50%, however, the soil's liquefaction potential is reduced [27].

Zhou et al. [27] concluded that the cone tip resistance (q_c) factor is sensitive among the predictor variables in CPT in-situ test method, which provides meaningful guiding significance for the subsequent prediction of seismic liquefaction potential. Furthermore Ahmad et al. [18] concluded that cone tip resistance (q_c) has a considerable influence on liquefaction triggering. Furthermore, Ahmad et al. [28] used the equivalent clean sand penetration resistance (q_{c1Ncs}) to decrease uncertainty and has found the strongest influence on liquefaction potential.

3.1.3 Site condition

It is widely known that the increase in the vertical effective stress increases the bearing capacity and shear strength of soil, and consequently increases the shear stress required to cause liquefaction and decreases the potential for liquefaction. Many researchers have reported that saturated sands deeper than 15 to 18 m are not probably to liquefy [29]. These depths are in general agreement to Kishada [30], who states that a saturated sandy soil is not liquefiable if the value of the vertical effective stress exceeds 190 kN/m^2. It is reported that an increase in the overburden pressure the occurrence of liquefaction decreases [31, 32]. Tesfamariam and Liu [20] considered the Stark and Olson [21] earthquake liquefaction datasets and, intuited that, with a decrease in vertical effective stress, the likelihood of soil liquefaction increases. As vertical effective stress is conditioned on total vertical stress therefore accordingly, total and vertical effective stresses are included in the proposed model as governing factors.

In order to induce extensive damage at ground surface level due to liquefaction, the liquefied soil layer must be sufficient thick thereby resulting uplift pressure and amount of water expelled from the liquefied layer can result in ground damage such as sand boiling and fissuring (Ishihara [26]; Dobry [33]). If the liquefied sand layer is thin and deposited within the soil profile, the presence of a non-liquefiable surface layer may prevent the effects of the at-depth liquefaction from reaching the surface. Ishihara [26] established a standard that specifies a threshold value for the thickness of a non-liquefiable surface layer to avoid ground damage due to liquefaction.

It was intuited in the survey report prepared by Japan society of Civil Engineers that the big-sized earthquake liquefied the sand layer when the thickness is more than 3.0 m. When the thickness of the liquefied layer is very thin, the presence of a non-liquefiable surface layer may prevent the effects of the in-depth liquefaction from reaching the surface.

The resistance of soil to liquefaction is weakened as groundwater levels rise. The effect on soil liquefaction potential increases as groundwater levels rise above 2 m [34]. The water table regime must be minimized as one of the design criteria against seismic soil liquefaction [35]. The vertical effective stress is closely related to the depth of soil deposit. The vertical effective stress increases as the depth of the soil deposit increases. Increased vertical stress has been shown to improve the soil's bearing capacity and shear strength, reducing the risk of liquefaction. Even liquefaction from very loose sand is almost impossible for over 15 m of overburden, according to Florin and Ivanov [36], and Satyam [37] concluded the same for the preliminary assessment of the soil liquefaction potential in a seismically active region.

The significant factors of seismic soil liquefaction that are identified through SLR approach are presented in **Table 2**.

Field experts' examined and analyzed the preliminary list and they believed that the soil liquefaction factors retrieved from the literature were important for expanding exploratory research by developing structural self-interaction matrix for interpretive structural modeling. The set of liquefaction factors identified in **Table 2** for seismic soil liquefaction potential was used to develop the model which represented the correlation between eleven seismic soil liquefaction factors. In the ISM model, for the development of the structural self-interaction matrix (SSIM),

Factor (F_i) code	Significant factor
F_1	Earthquake magnitude, (M)
F_2	Peak ground acceleration, ($a_{\max}$)
F_3	Closest distance to rupture surface, (R/r_{rup})
F_4	Fines content, (FC)
F_5	Equivalent clean sand penetration resistance, (q_{c1Ncs})
F_6	Soil behavior type index, (I_c)
F_7	Vertical effective stress, (σ'_v)
F_8	Total vertical stress, (σ_v)
F_9	Groundwater table, (D_w)
F_{10}	Depth of soil deposit, (D_s)
F_{11}	Thickness of soil layer, (T_s)

Table 2.
List of significant factors of seismic soil liquefaction.

F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}	F_i
	V	O	O	O	O	O	O	O	O	O	V	F_1
		A	O	O	A	O	O	O	O	O	V	F_2
			O	O	O	O	O	O	O	O	V	F_3
				V	V	O	O	O	O	O	V	F_4
					A	A	O	A	A	O	V	F_5
						A	A	O	O	O	V	F_6
							A	A	A	O	V	F_7
								O	A	O	V	F_8
									O	O	V	F_9
										O	V	F_{10}
											V	F_{11}
												F_{12}

Note: V–row factor influences the column factor; A–column factor influences the row factor; O–no relationship between the row and column factors.

Table 3.
Structural self-interaction matrix for seismic soil liquefaction factors.

pair-wise comparison were made by the correlation criteria and four symbols V, A, X, or O were used (see **Table 3**). For example, earthquake magnitude F_1 (M)–row factor influences the peak ground acceleration, F_2 ($a_{\max}$)– column factor so the symbol used is V. Groundwater table depth F_9 (D_w)–column factor influences the vertical effective stress, F_7 (σ'_v)–row factor so the symbol used is A. Earthquake magnitude F_1 (M)–row factor has no relation with the thickness of soil layer F_{11} (T_s)–column factor so the symbol used is O. Field experts' made consensus on the pair-wise comparison and the results are shown in **Table 3**.

SSIM is converted to a binary matrix called the initial reachability matrix by replacing the original symbols V, A, X, and O with 1 or 0 (**Table 4**) as per the rule illustrated in **Table 1**. When pair of the same factor, i.e., F_1 (M) with F_1 (M) is formed, it is represented by 1. The concept of transitivity is introduced in **Table 4**

F_i	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}
F_1	1	1	0	0	0	0	0	0	0	0	0	1
F_2	0	1	0	0	0	0	0	0	0	0	0	1
F_3	0	1	1	0	0	0	0	0	0	0	0	1
F_4	0	0	0	1	1	1	0	0	0	0	0	1
F_5	0	0	0	0	1	0	0	0	0	0	0	1
F_6	0	1	0	0	1	1	0	0	0	0	0	1
F_7	0	0	0	0	1	1	1	0	0	0	0	1
F_8	0	0	0	0	0	1	1	1	0	0	0	1
F_9	0	0	0	0	1	0	1	0	1	0	0	1
F_{10}	0	0	0	0	1	0	1	1	0	1	0	1
F_{11}	0	0	0	0	0	0	0	0	0	0	1	1
F_{12}	0	0	0	0	0	0	0	0	0	0	0	1

Table 4.
Initial reachability matrix.

F_i	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}	Dri.	Rank
F_1	1	1	0	0	0	0	0	0	0	0	0	1	3	III
F_2	0	1	0	0	0	0	0	0	0	0	0	1	2	II
F_3	0	1	1	0	0	0	0	0	0	0	0	1	3	III
F_4	0	1*	0	1	1	1	0	0	0	0	0	1	5	V
F_5	0	0	0	0	1	0	0	0	0	0	0	1	2	II
F_6	0	1	0	0	1	1	0	0	0	0	0	1	4	IV
F_7	0	1*	0	0	1	1	1	0	0	0	0	1	5	V
F_8	0	1*	0	0	1*	1	1	1	0	0	0	1	6	VI
F_9	0	0	0	0	1	1*	1	0	1	0	0	1	5	V
F_{10}	0	0	0	0	1	1*	1	1	0	1	0	1	6	VI
F_{11}	0	0	0	0	0	0	0	0	0	0	1	1	2	II
F_{12}	0	0	0	0	0	0	0	0	0	0	0	1	1	I
Dep.	1	7	1	1	7	6	4	2	1	1	1	12	44/44	
Rank	VI	II	VI	VI	II	III	IV	V	VI	VI	VI	I		VI/VI

Note: 1 indicates the values after applying transitivity; Dep. represents dependence power; Dri. represents driving power.*

Table 5.
Final reachability matrix.

when the initial reachability matrix has been obtained and is presented in final reachability matrix (**Table 5**), wherein entries marked (*) show the transitivity. For example, in **Table 4**, the initial reachability matrix shows that F_4 (FC) is related to F_6 (I_c), and F_6 (I_c) is related to F_2 ($a_{\max}$), then the interaction F_4 (FC) and F_2 ($a_{\max}$) having 0 value is transformed into 1* in **Table 5**. The reachability sets are determined from the factor itself and other factors which have influence in the horizontal direction, while the antecedent sets consist of the factor itself and other factors which have influence in the vertical direction for each significant soil liquefaction factor. For example, in the case of F_1 (M) in the final reachability matrix (**Table 5**), the reachability set will be all factors with values of 1 or 1* in the row intersections with F_1 (M): F_1 (M), F_2 (a_{max}), and F_{12} (LP). The antecedent set is all factors with values of 1 or 1* in the column intersections with F_1 (M): F_1 (M) only. When the intersection and reachability sets appear in the same intersection and reachability columns, then the corresponding factor is confirmed at a level (e.g. F_{12} (LP) as level 1) and the factor in that level is separated out, e.g. F_{12} (LP) from the other factors for the next level-iteration process.

The same level-iteration process is repeated until the level of each seismic soil liquefaction factor is established. Level partitioning of the soil liquefaction factors is accomplished in six iterations and shown in **Tables 6–11**. The ISM model is developed on the level partitions basis from **Tables 6–11**.

Factor (F_i)	Reachability set $R(F_i)$	Antecedent set $A(F_i)$	Intersection set $R(F_i) \cap A(F_i)$	Level L_i
F_1	F_1,F_2,F_{12}	F_1	F_1	
F_2	F_2,F_{12}	$F_1,F_2,F_3,F_4,F_6,F_7,F_8$	F_2	
F_3	F_2,F_3,F_{12}	F_3	F_3	
F_4	F_2,F_4,F_5,F_6,F_{12}	F_4	F_4	
F_5	F_5,F_{12}	$F_4,F_5,F_6,F_7,F_8,F_9,F_{10}$	F_5	
F_6	F_2,F_5,F_6,F_{12}	$F_4,F_6,F_7,F_8,F_9,F_{10}$	F_6	
F_7	F_2,F_5,F_6,F_7,F_{12}	F_7,F_8,F_9,F_{10}	F_7	
F_8	$F_2,F_5,F_6,F_7,F_8,F_{12}$	F_8,F_{10}	F_8	
F_9	F_5,F_6,F_7,F_9,F_{12}	F_9	F_9	
F_{10}	$F_5,F_6,F_7,F_8,F_{10},F_{12}$	F_{10}	F_{10}	
F_{11}	F_{11},F_{12}	F_{11}	F_{11}	
F_{12}	F_{12}	$F_1,F_2,F_3,F_4,F_5,F_6,F_7,F_8,F_9,F_{10},F_{11},F_{12}$	F_{12}	L_1

Table 6.
Level partition—Iteration 1.

Factor (F_i)	Reachability set $R(F_i)$	Antecedent set $A(F_i)$	Intersection set $R(F_i) \cap A(F_i)$	Level L_i
F_1	F_1,F_2	F_1	F_1	
F_2	F_2	$F_1,F_2,F_3,F_4,F_6,F_7,F_8$	F_2	L_2
F_3	F_2,F_3	F_3	F_3	
F_4	F_2,F_4,F_5,F_6	F_4	F_4	
F_5	F_5	$F_4,F_5,F_6,F_7,F_8,F_9,F_{10}$	F_5	L_2
F_6	F_2,F_5,F_6	$F_4,F_6,F_7,F_8,F_9,F_{10}$	F_6	
F_7	F_2,F_5,F_6,F_7	F_7,F_8,F_9,F_{10}	F_7	
F_8	F_2,F_5,F_6,F_7,F_8	F_8,F_{10}	F_8	
F_9	F_5,F_6,F_7,F_9	F_9	F_9	
F_{10}	F_5,F_6,F_7,F_8,F_{10}	F_{10}	F_{10}	
F_{11}	F_{11}	F_{11}	F_{11}	L_2

Table 7.
Level partition—Iteration 2.

Factor (F_i)	Reachability set $R(F_i)$	Antecedent set $A(F_i)$	Intersection set $R(F_i) \cap A(F_i)$	Level L_i
F_1	F_1	F_1	F_1	L_3
F_3	F_3	F_3	F_3	L_3
F_4	F_4,F_6	F_4	F_4	
F_6	F_6	$F_4,F_6,F_7,F_8,F_9,F_{10}$	F_6	L_3
F_7	F_6,F_7	F_7,F_8,F_9,F_{10}	F_7	
F_8	F_6,F_7,F_8	F_8,F_{10}	F_8	
F_9	F_6,F_7,F_9	F_9	F_9	
F_{10}	F_6,F_7,F_8,F_{10}	F_{10}	F_{10}	

Table 8.
Level partition—Iteration 3.

Factor (F_i)	Reachability set $R(F_i)$	Antecedent set $A(F_i)$	Intersection set $R(F_i) \cap A(F_i)$	Level L_i
F_4	F_4	F_4	F_4	L_4
F_7	F_7	F_7,F_8,F_9,F_{10}	F_7	L_4
F_8	F_7,F_8	F_8,F_{10}	F_8	
F_9	F_7,F_9	F_9	F_9	
F_{10}	F_7,F_8,F_{10}	F_{10}	F_{10}	

Table 9.
Level partition—Iteration 4.

Factor (F_i)	Reachability set $R(F_i)$	Antecedent set $A(F_i)$	Intersection set $R(F_i) \cap A(F_i)$	Level L_i
F_8	F_8	F_8,F_{10}	F_8	L_5
F_9	F_9	F_9	F_9	L_5
F_{10}	F_8,F_{10}	F_{10}	F_{10}	

Table 10.
Level partition—Iteration 5.

Factor (F_i)	Reachability set $R(F_i)$	Antecedent set $A(F_i)$	Intersection set $R(F_i) \cap A(F_i)$	Level L_i
F_{10}	F_{10}	F_{10}	F_{10}	L_6

Table 11.
Level partition—Iteration 6.

The digraph is developed from final reachability matrix by removing the transitivity links and on the level partitions basis from **Tables 6–11**. The digraph is converted in to an ISM-based hierarchical model by replacing nodes with statements. Each seismic soil liquefaction factor is positioned as per the consequent level and the relationships of the soil liquefaction factors are fixed from the bottom (level 6) to the top of the model (level 1). The seismic soil liquefaction factors are connected by arrows from the bottom of the model (higher-level) to the top of model (lower-level). The multilevel hierarchy model developed with identified relations between the significant factors of seismic soil liquefaction potential (LP) is shown in **Figure 1**.

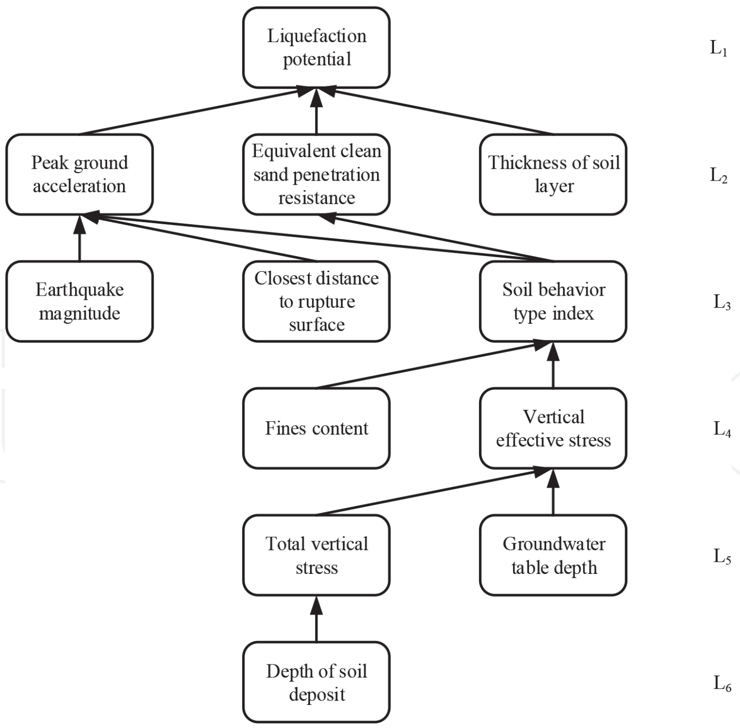

Figure 1.
Model depicting the relationships between seismic soil liquefaction significant factors based on ISM technique.

3.2 MICMAC analysis: classification of CPT-based seismic soil liquefaction significant factors

The driving power and dependency power of each variable was measured using the final reachability matrix to analyze the strength of the relationship between seismic soil liquefaction significant factors. Driving power is characterized as an activity that propels other activities, while dependency power is defined as an activity that is driven by other activities. The driving power and dependency power are determined from the final reachability matrix by adding the sum of all '1's in that factor's corresponding row and column.

This is considered as an input to build a graph to classify the factors into four clusters i.e., Autonomous, Dependent, Linkage, and Independent factors (see **Figure 2**). Autonomous factors (first cluster) have weak driving power and weak dependence power. Dependent factors (second cluster) have weak driving power and strong dependence power. Linkage factors (third cluster) have strong driving power and strong dependence power. In the dependent factors (fourth cluster) acquires strong driving power and weak dependence power. The soil liquefaction factors have been categorized based on these aforementioned clusters. The four clusters of soil liquefaction factors are:

3.2.1 Cluster I: autonomous factors

Cluster I, represents autonomous factors and consists of soil liquefaction factors which have weak driving power and dependence power. This cluster has six seismic soil liquefaction factors (55%). Cluster I factors are relatively disconnected from the system. Autonomous factors in cluster I are earthquake magnitude F_1 (M), closest distance to rupture surface F_3 (R/r_{rup}), fines content F_4 (FC), vertical effective stress F_7 (σ'_v), groundwater table F_9 (D_w), and thickness of soil layer F_{11} (T_s).

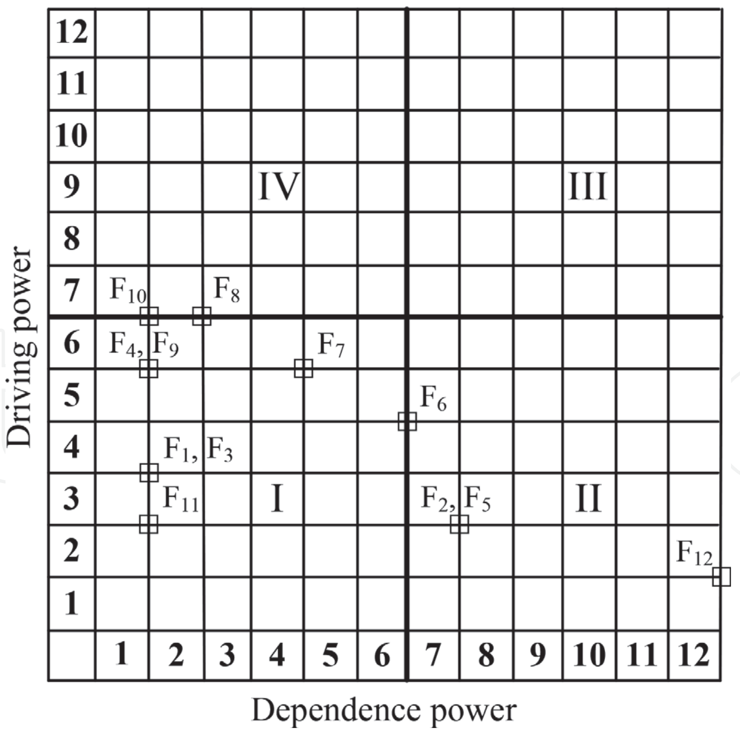

Figure 2.
MICMAC Analysis of seismic soil liquefaction factors.

3.2.2 Cluster II: dependence factors

Dependence factors have a strong dependence power and weak driving power. This dependence cluster has two seismic soil liquefaction factors (18%) except liquefaction potential that including peak ground acceleration F_2 ($a_{\max}$) and equivalent clean sand penetration resistance F_5 (q_{c1Ncs}), while, the liquefaction potential F_{12} (LP) falls in this cluster is not an influence factor of earthquake liquefaction, but a discriminate index. It is just proved that the driving power is poor and needs to rely on other factors to discernment liquefaction. In the ISM model, these factors form the top levels which need other soil liquefaction factors that collectively act to influence soil liquefaction.

3.2.3 Cluster III: linkage factors

Linkage factors have a strong driving power as well as strong dependence power. The factors affect each other and directly affect the liquefaction system. Therefore, the factors in this cluster are unstable. No factor in this model fall into this cluster, which indicates that the liquefaction influencing factors in this model are relatively stable.

3.2.4 Cluster IV: independent/driving factors

In this cluster, factors have strong driving power but weak dependence power. It is often the most critical factors of the system and also the essential factors. No factor in this model fall in this cluster.

A special case can be observed on factors that are depth of soil deposit F_{10}, (D_s) and total vertical stress F_8, (σ_v), on the middle between independent and autonomous factors whereas soil behavior type index F_6, (I_c), on the middle between dependence and autonomous factors. Factors that are depth of soil deposit F_{10}, (D_s) and total vertical stress F_8, (σ_v), are lower on dependence but higher on driving power, are located between two clusters, I and IV. Similarly, soil behavior type index F_6, (I_c), factor is intermediate on dependence but lower driving power, but is located between two clusters, I and II. These factors need attention owing to establish and provide a more accurate and caution way of selecting significant factors for seismic soil liquefaction potential and its induced-hazards risk lassessment modeling.

4. Discussion and conclusions

The intention of this research study is the identification and benchmarking the seismic soil liquefaction factors of seismic soil liquefaction and the understanding of their relationship. ISM-based hierarchical model has been developed to examine the cone penetration test based significant factors of seismic soil liquefaction potential. The ISM model presents the relationships between seismic soil liquefaction factors and their benchmarking position from higher to lower-level significant factors in hierarchy. The results provide a more accurate and caution way for establishment of seismic soil liquefaction potential and liquefaction-induced hazards risk assessment models. Seismic soil liquefaction factors located on top level hierarchy are greatly influenced by the interconnection of left-over factors. It is evident from the ISM model that the factor depth of soil deposit, F_{10} (D_s) at level 6, forms the base of the ISM hierarchy and has high driving power and low dependence power, whereas peak ground acceleration F_2 ($a_{\max}$), equivalent clean sand penetration resistance F_5 (q_{c1Ncs}), and thickness of soil layer F_{11} (T_s), in the second level directly influence liquefaction potential. The other soil liquefaction potential factors are earthquake magnitude F_1 (M), closest distance to rupture surface F_3 (R/r_{rup}), and soil behavior type index F_6 (I_c) at level 3, fines content F_4 (FC) and vertical effective stress F_7 (σ'_v) at level 4, total vertical stress F_8 (σ_v) and groundwater table depth F_9 (D_w) at level 5, as per the outcomes of the ISM hierarchical model and are classified as indirect factors that affect soil liquefaction.

By performing MICMAC analysis, the dependence-driving diagram is plotted which offers information about the relative significance and the interdependencies among various factors of seismic soil liquefaction. It is found in this study, that there exists no independent and linkage factor. Among the 11 factors studied, 2 factors are falling in dependent quadrant in the dependence-driving diagram and it is recognized that these particular factors will depend on other factors. Further, 6 factors fall under the autonomous quadrant. Rest of the 3 factors, in which 2 of them i.e., depth of soil deposit F_{10}, (D_s) and total vertical stress F_8, (σ_v), are located between two clusters, I and IV owing to intermediate diving power. Similarly, soil behavior type index F_6, (I_c), is located between two clusters, I and II owing to intermediate dependence power. These factors i.e., depth of soil deposit, total vertical stress and soil behavior type index need attention owing to provide a more accurate and caution way for further establishment of seismic soil liquefaction potential and liquefaction-induced hazards risk assessment models.

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Conflict of interest

The authors declare no conflict of interest.

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References

[1] Dalvi, A.N.; Pathak, S.R.; Rajhans, N. R. Entropy analysis for identifying significant parameters for seismic soil liquefaction. *Geomechanics and Geoengineering* **2014**, *9*, 1-8.

[2] Zhu, S. Statistical analysis of factors causing liquefaction of sand during Tangshan Earthquake. *Seismology and Geology* **1980**, *2*, 79-80.

[3] Tang, X.-W.; Hu, J.-L.; Qiu, J.-N. Identifying significant influence factors of seismic soil liquefaction and analyzing their structural relationship. *KSCE Journal of Civil Engineering* **2016**, *20*, 2655-2663.

[4] Ahmad, M.; Tang, X.-W.; Qiu, J.-N.; Ahmad, F. Interpretive Structural Modeling and MICMAC Analysis for Identifying and Benchmarking Significant Factors of Seismic Soil Liquefaction. *Applied Sciences* **2019**, *9*, 233.

[5] Okoli, C.; Schabram, K. A guide to conducting a systematic literature review of information systems research. Working Papers on Information Systems **2010**, *10*, 1-51.

[6] Tranfield, D.; Denyer, D.; Smart, P. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *Br. J. Manage.* **2003**, *14*, 207-222.

[7] Olsen, S. *Group Planning and Problem-Solving Methods in Engineering Management*; John Wiley & Sons, Inc., 605 3rd Ave., New York, NY 10158: 1982.

[8] Sushil, S. Interpreting the interpretive structural model. *Global Journal of Flexible Systems Management* **2012**, *13*, 87-106.

[9] Warfield, J.N. Developing interconnection matrices in structural modeling. *IEEE Transactions on Systems, Man, and Cybernetics* **1974**, *SMC-4*, 81-87.

[10] Pfohl, H.-C.; Gallus, P.; Thomas, D. Interpretive structural modeling of supply chain risks. *International Journal of Physical Distribution & Logistics Management* **2011**, *41*, 839-859.

[11] Saxena, J.; Vrat, P. Impact of indirect relationships in classification of variables—a micmac analysis for energy conservation. *Systems Research* **1990**, *7*, 245-253.

[12] Fink, A. *Conducting research literature reviews: From the internet to paper*; Sage publications: 2019.

[13] Seed, H.B. Ground motions and soil liquefaction during earthquakes. *Earthquake engineering research insititue* **1982**.

[14] Pirhadi, N.; Tang, X.; Yang, Q.; Kang, F. A New Equation to Evaluate Liquefaction Triggering Using the Response Surface Method and Parametric Sensitivity Analysis. *Sustainability* **2019**, *11*, 112.

[15] Ahmad, M.; Tang, X.-W.; Qiu, J.-N.; Ahmad, F.; Gu, W.-J. A step forward towards a comprehensive framework for assessing liquefaction land damage vulnerability: Exploration from historical data. *Frontiers of Structural and Civil Engineering* **2020**, *14*, 1476-1491.

[16] Hu, J.-L.; Tang, X.-W.; Qiu, J.-N. Assessment of seismic liquefaction potential based on Bayesian network constructed from domain knowledge and history data. *Soil Dyn. Earthquake Eng.* **2016**, *89*, 49-60.

[17] Ahmad, M.; Tang, X.-W.; Ahmad, F.; Jamal, A. Assessment of soil liquefaction potential in Kamra, Pakistan. *Sustainability* **2018**, *10*, 4223.

[18] Ahmad, M.; Tang, X.-W.; Qiu, J.-N.; Gu, W.-J.; Ahmad, F. A hybrid approach for evaluating CPT-based seismic soil

liquefaction potential using Bayesian belief networks. *Journal of Central South University* **2020**, *27*, 500-516.

[19] Green, R.A.; Bommer, J.J. What is the smallest earthquake magnitude that needs to be considered in assessing liquefaction hazard? *Earthquake Spectra* **2019**, *35*, 1441-1464.

[20] Tesfamariam, S.; Liu, Z. Seismic risk analysis using Bayesian belief networks. In *Handbook of seismic risk analysis and management of civil infrastructure systems*, Elsevier: 2013; pp. 175-208.

[21] Stark, T.D.; Olson, S.M. Liquefaction resistance using CPT and field case histories. *Journal of geotechnical engineering* **1995**, *121*, 856-869.

[22] Boore, D.M.; Joyner, W.B.; Fumal, T.E. Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work. *Seismol. Res. Lett.* **1997**, *68*, 128-153.

[23] Robertson, P.; Wride, C. Evaluating cyclic liquefaction potential using the cone penetration test. *Canadian geotechnical journal* **1998**, *35*, 442-459.

[24] Seed, H.B. Landslides during earthquakes due to liquefaction. *Journal of Soil Mechanics & Foundations Div* **1968**.

[25] Andrus, R.; Stokoe, K.H.; Roesset, J. Liquefaction of gravelly soil at Pence Ranch during the 1983 Borah Peak, Idaho earthquake. *International Journal of Rock Mechanics and Mining Sciences Abstracts* **1993**, *30*, 98A.

[26] Ishihara, K. Stability of natural deposits during earthquakes. Proceeding of the 11th conference. In Proceedings of Soil Mechanics and Foundation Engineering, San Francisco.

[27] Zhou, J.; Li, E.; Wang, M.; Chen, X.; Shi, X.; Jiang, L. Feasibility of stochastic gradient boosting approach for evaluating seismic liquefaction potential based on SPT and CPT case histories. *J. Perform. Constr. Facil.* **2019**, *33*, 04019024.

[28] Ahmad, M.; Tang, X.-W.; Qiu, J.-N.; Ahmad, F. Evaluating Seismic Soil Liquefaction Potential Using Bayesian Belief Network and C4. 5 Decision Tree Approaches. *Applied Sciences* **2019**, *9*, 4226.

[29] *Liquefaction potential of cohesionless soils. 2007. GDP-9, Revision# 2, State of New York, Department of Transportation*; Procedure, Geotechnical Design, Geotechnical Engineering Bureau: 2007.

[30] Kishada, H. A note on liquefaction of hydraulic fill during the Tokachi-Oki earthquake. In Proceedings of Second Seminar on Soil Behavior and Ground Response During Earthquakes, University of California, Berkeley, CA.

[31] Boulanger, R.W. High overburden stress effects in liquefaction analyses. *Journal of Geotechnical and Geoenvironmental Engineering* **2003**, *129*, 1071-1082.

[32] Seed, R.B.; Cetin, K.O.; Moss, R.E.; Kammerer, A.M.; Wu, J.; Pestana, J.M.; Riemer, M.F.; Sancio, R.B.; Bray, J.D.; Kayen, R.E. Recent advances in soil liquefaction engineering: a unified and consistent framework. In Proceedings of Proceedings of the 26th Annual ASCE Los Angeles Geotechnical Spring Seminar: Long Beach, CA.

[33] Dobry, R. Some Basic Aspects of Soil Liquefaction during Earthquakes a. *Ann. N. Y. Acad. Sci.* **1989**, *558*, 172-182.

[34] Hannich, D.; Hoetzl, H.; Ehret, D.; Huber, G.; Danchiv, A.; Bretotean, M. Liquefaction probability in Bucharest and influencing factors. In Proceedings of Proceedings of the International

Symposium on Strong Vrancea Earthquake and Risk Mitigation, Bucharest, Romania; pp. 4-6.

[35] Fioravante, V.; Giretti, D.; Abate, G.; Aversa, S.; Boldini, D.; Capilleri, P. P.; Cavallaro, A.; Chamlagain, D.; Crespellani, T.; Dezi, F. Earthquake geotechnical engineering aspects of the 2012 Emilia-Romagna earthquake (Italy). In Proceedings of Case histories in geotechnical engineering, Chicago; pp. 1-34.

[36] Florin, V.; Ivanov, P. Liquefaction of saturad sandy soils. In Proceedings of Proc. 5th Int. Soil Mech. Foundat. Eng., Paris; p. 111.

[37] Satyam, N. Review on liquefaction hazard assessment. In *Advances in Geotechnical Earthquake Engineering—Soil Liquefaction and Seismic Safety of Dams and Monuments*, 2012; pp. 63-82.