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Soil and foundation stability improvement by stone column: A case study in Adapazari city, Turkey

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Adapazari city is located on a very deep alluvial deposit and in a seismically active region. Due to the catastrophic earthquakes, the region had painful experiences in the past. The latest severe earthquake, called Marmara earthquake, hit the region on August 17, 1999. It resulted in nearly 4,000 deaths, over 5,000 injuries and totally destroyed more than 29,000 buildings. The region has liquefaction potential due to its geological set up. Most of the structures built on the liquefiable soil severely settled or tilted besides the structural damages. To re-accommodate these structures, it is necessary to strengthen them besides improve their ground conditions. Then, it may be possible to avoid probable damages caused by liquefaction and use them again safely. In this study, application of modified dry bottom feed stone column as one of the dominant ground improvement methods in the region was introduced. Also, a numerical analysis is carried out to check its performance with respect to displacements. According to numerical results, significant improvements were obtained in terms of displacements.

Key words: Marmara earthquake, alluvial deposit, ground improvement, stone column, numerical model.

INTRODUCTION

There are a number of methods available to improve ground conditions such as stone columns, jet grouting, compaction grouting, short pile, dynamic compaction, lime stabilization etc. Before using any of these methods, it is required to know the local ground conditions in detail. Even though processes are costly and time consuming they must be done in order to choose a most suitable and applicable ground improvement method to mitigate the undesirable consequences caused by earthquakes.

In Adapazari region, due to local site conditions, most widely accepted ground improvement techniques have limitations. Selecting a suitable and effective ground improvement method is very important. Stone column, cement-grouting with chemicals and reinforced short pile are the three alternative solutions, which are used extensively in the region. Besides local ground conditions, economical considerations and level of earthquake's da-

gages or existing status should be evaluated carefully.

Stone column is an acceptable technique for improving soil conditions. This method has been used since late 1950s. Through the application of this method, it may be possible to limit settlement and increase the strength of foundation. During an earthquake, stone columns can also act as a gravel drain column to release pore water pressure and the liquefaction potential of a ground can be reduced (Gnieal and Bouazza, 2008; Shenthan et al., 2004; Mitra and Chathpadhyay, 1999; Madhav and Miura, 1994; Goughnour et al., 1991; Mitchel et al., 1985; Datye, 1982).

The possible benefits of stone columns include densification of surrounding non-cohesive soil, dissipation of excess pore water pressure and re-distribution of earthquake-induced or pre-existing stress (due to introduction of the stiffer columns). When dealing with non-plastic silty soils, only the third benefit can be expected primarily to mitigate liquefaction (Adalier et al., 2003).

One of the techniques extensively used in soft soils is vibro replacement, which consists of replacing some of the soft soil with crushed rock or gravel to form an array of stone columns beneath the foundation. The use of

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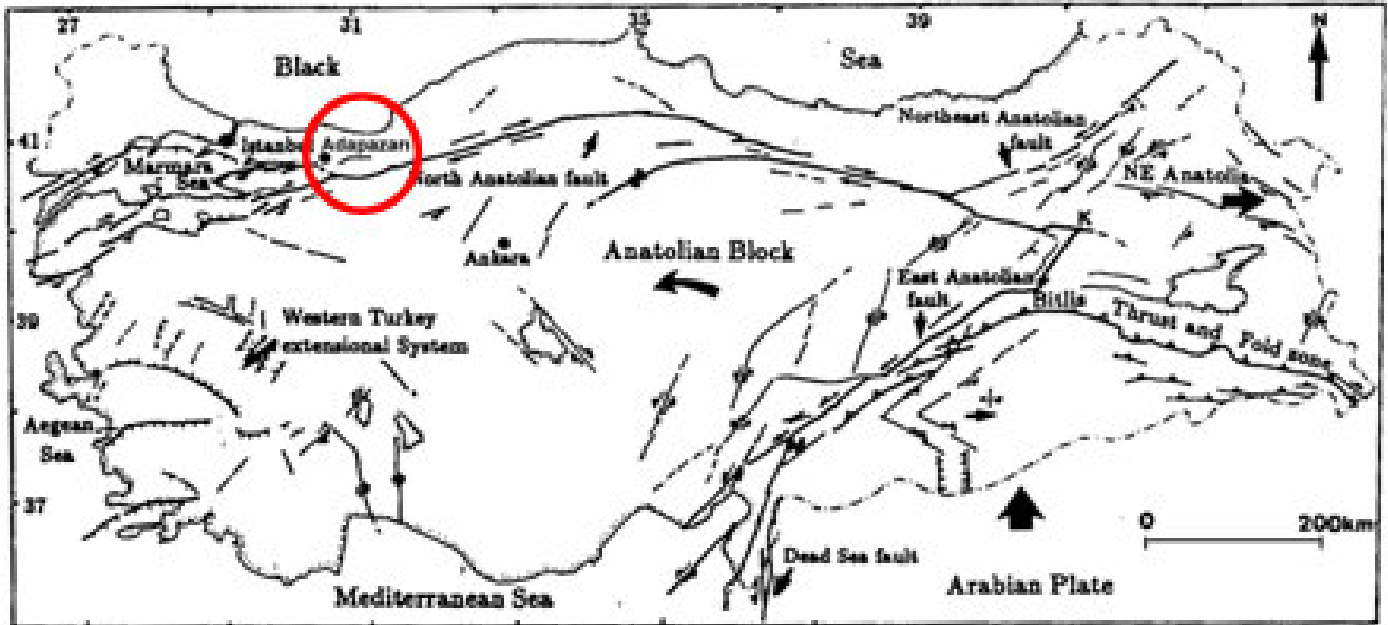


Figure 1. Location of study area and major tectonic elements of Turkey (Barka and Kadinsky-Code, 1988).

conventional stone columns in soft soil deposits was found to benefit foundations in many respects (Gniel and Bouazza, 2008).

Alternatively, soil condition can also be improved by injecting a fluidized material such as cement paste suspension or a chemical solution known as grout. Permeability of soil decreases and soil becomes stiffer and stronger. To penetrate the grout into voids among soil particles, certain amount of pressure is required. By increasing the viscosity of grout, porous size can be decreased (Powrie, 1997).

Reinforced short pile is also considered as one of alternative methods to improve the stability of the structure and avoid the liquefaction damages to the structures. The length and diameter of the reinforced short pile are important in application (Cernica, 1995).

The main objective of this paper is to introduce the modified dry bottom feed stone column installation method under existing buildings, which were mostly damaged by various levels. In this study, a numerical analysis is also carried out to observe its applicability, merits, advantages and disadvantages.

GEOLOGY AND LOCAL GROUND CONDITIONS OF ADAPAZARI REGION

The study area is located on the North Anatolian Fault (NAF), which is the largest and most active one in Turkey (Şengör, 1980; Barka and Gülen, 1987; Barka and Kadinsky-Code, 1988) (Figure 1). Adapazari city, in parti-

cular, is founded on very deep alluvial deposits consisting mostly gravel, sand, silt, silty and clayey sands, clay and aged Quaternary. The Sakarya River, which is one of the biggest rivers in Turkey, flows through Adapazari valley. It is considered that deep alluvial deposits are formed by the river.

Due to the great influence of the regime of Sakarya River in the region, ground layer exhibits lens kind deposit. Generally, silt and clay series exist on the ground and gravel-sand-silt series continuously follow the surface series. The ground dominantly consists of gravely and silty sand with different densities and contains low plasticity silty and clay bandage at some places (Tezcan, 1975). Groundwater table in Adapazari region exhibits differences and comes close to ground surface during spring seasons.

The test site consists of thick alluvial deposits that are transported by the river. Area covered by water was filled by floods of the Sakarya River that occurs nearly every 2 years. At present, almost all the area is developed to be a flat area and marsh is seldom seen. As indicated in this geological history, surface soil of the area is a very young Holocene soil developed in the recent 200 years. The water table is generally high to be about 1 - 3 m and it may come closer the ground surface in rainy season (Çelebi et al., 2009).

Especially after the earthquake, a number of borehole logs drilled by various governmental agencies, local public body and private consultants are available. The depth of these boreholes ranges from 10 to 200 meters. A typical borehole data obtained from the region are given

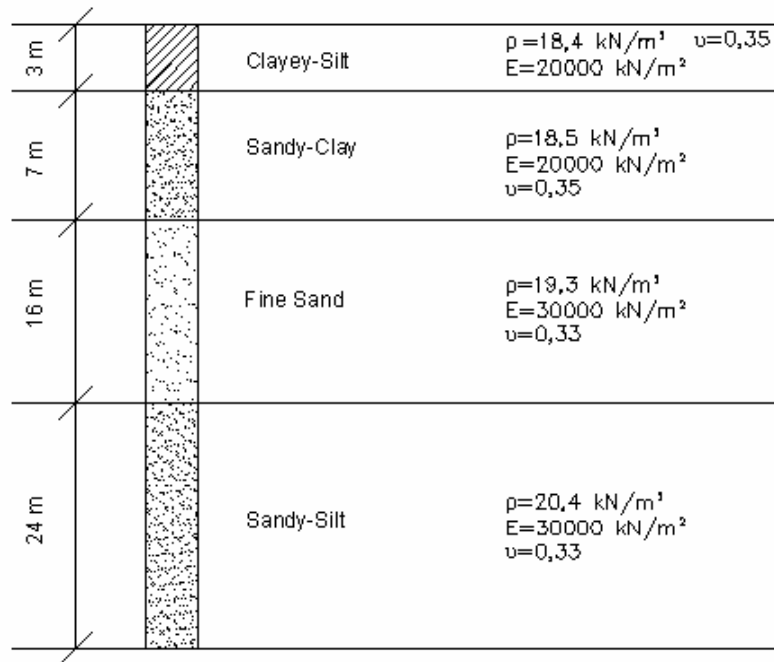


Figure 2. Typical ground cross-section of Adapazari region.

in Figure 2. In addition, some deep boreholes drilled at Adapazari Valley failed to reach bedrock. Because of its geology and local ground conditions, the valley receives a great attention for its liquefaction potential during earthquakes (Bray et al., 2004; Arman et al., 1997).

SEISMICITY AND IMPORTANT EARTHQUAKES OCCURRED IN ADAPAZARI REGION

Turkey is on the Alpine active earthquake chain. 1939 Erzincan, 1966 Varto, 1967 Adapazari-Mudurnu, 1970 Gediz, 1971 Burdur and Bingöl, 1992 Erzincan, 1995 Dinar and 1999 Marmara earthquakes are examples of Alpine chain activity. The NAF, a well-known strike-slip fault, lies from east to west. Adapazari City is located on the north side of the NAF and had experienced severe earthquakes in the past. According to historical records, earthquakes affected the region and caused extensive damages and casualties. Hendek earthquake in 1943 ($M_s = 6.4$), Abant earthquake in 1957 ($M_s = 7.0$), Mudurnu Valley earthquake ($M_s = 7.1$) and Marmara earthquake ($M_s = 7.8$) are the biggest and destructive ones in the region.

Mudurnu earthquake occurred on July 22, 1967 in the western part of the NAF zone. The sense of movement along the fault break was high lateral with the north side downthrown. The maximum relative lateral and vertical displacements were 190 and 120 cm. The earthquake killed 86 and wounded 332 people, destroyed over 5000 houses (Ambraseys, 1988).

The Marmara earthquake of August 17, 1999 was the

most recent destructive event in the region. It was associated with faulting over a length of approximately 100-120 km. The maximum lateral displacement along this fault line in Adapazari region was approximately 425 cm and the maximum vertical displacement was approximately 30 cm. Most of the reinforced concrete structures, built on the liquefiable soil in the region, were severely settled or tilted besides the structural damages (Figure 3) (Bakir et al., 2002, 2005; Wasti and Ozcebe, 2003; Mollamahmutoglu et al., 2002).

Only in the region, 29,824 buildings were heavily damaged or totally collapsed, 22,170 buildings were medium damaged and 29,938 buildings were slightly damaged. Official records indicated that 3,891 deaths and 5,150 injuries were recorded in Adapazari city itself (Governor of Sakarya, 2000). The Marmara earthquake was felt in a very large area. However, Adapazari region was the worst affected area due to its bad soil conditions compared to the neighbouring regions geology and local ground conditions, the valley receives a great attention for its liquefaction potential during earthquakes (Bray et al., 2004; Arman et al., 1997).

GROUND IMPROVEMENT METHODS APPLIED IN ADAPAZARI REGION

During the Marmara earthquake, reinforced concrete structures, that were mostly 2 to 5 stories located on the surface of liquefiable soil, were severely settled or tilted due to the loss of bearing capacity of the soil. To retrofit these structures, it requires improving the existing soil



Figure 3. Totally damaged structure built on liquefiable soil.

condition with proper ground improvement methods and then repair by available engineering codes.

Two alternative solutions can be considered to avoid the effects of liquefaction-induced damages to the structures placed on a liquefiable soil;

- 1) To build a reliable structure that will not be affected by liquefaction phenomenon.
- 2) To improve ground condition that will avoid or minimize the liquefaction potential of a ground.

If it is possible, foundation of structure can be located under the liquefiable layer and pore water pressure, which increases dramatically during the earthquake, can be reduced or the characteristics of the ground can be changed. In addition to safety and reliability considerations, cost plays an important role as well in choosing a ground improvement method. Also, geometry of the structure is an important criterion.

In the region, three different ground improvement methods, grouting, reinforced short pile and stone column, were applied. Before a decision was made to pick a method, it was necessary to know ground conditions in detail. Based on the soil data, one of these methods was selected for an application. During the application, operating companies faced a number of difficulties. An important question was how safely and reliably ground condition of existing damaged structures could be improved. If there is no structure on a site, as usual it is straight forward to select a suitable method based on a detailed soil investigation. In Adapazari City, a ground improvement method must be done under an existing - either slightly or moderately damaged - structures. It was difficult to apply a suitable and reliable ground improvement method under this condition.

The grouting method is used to improve ground condition. For an application, it requires to drill boreholes with certain diameter, length and distance from each other under a damaged structure. Then, cement-based grout was injected to a ground under a certain pressure.

However, in most cases, it was difficult to place an ordinary boring machine under a damaged structure due to lack of enough space. Before grouting start, such difficulty should be eliminated. A special custom designed borehole machine was used to drill boreholes for grouting. Injection boreholes were approximately 76 mm in diameter and their length was ranged from 7 to 10 m.

However, in most cases, soil conditions in the region are not suitable for this method.

Reinforced short pile was also used to improve ground condition in the region. On site, similar difficulties were also faced. All reinforced short piles were fixed to a structure foundation. The diameter of the reinforced short pile was approximately 30 to 40 cm and their length is 7 to 15 m. Due to the soil condition of the region, there was no way to attach reinforced short piles to a reliable strata.

Komazawa et al. (2001) reported that the thickness of the alluvial deposit in the region was more than 1,000 m.

Application of modified dry bottom feed stone column, with approximately 40 to 60 cm in diameter and 5 to 10 m in length, was mostly done in the region. Besides borehole casing difficulties, similar problems were also encountered in the modified dry bottom feed stone column application. To drill approximately 20 cm diameter and 5 to 10 m length borehole requires a special boring machine. Boreholes with nearly 1.5 to 2.5 m distances from each other were drilled under damaged buildings. Then, boreholes were filled with crushed stone with certain size. Generally, in a liquefiable soil, when pore water pressure increases, a built up pressure will be reduced through stone columns. Then, structural damages caused by liquefaction will be minimized.

Application of modified dry bottom feed stone column

An application of stone column in the study area was different from an ordinary dry bottom feed stone column installation method which was detailed in literatures (Menard Soil Treatment, 2009; Terra Systems, 2009; The Vibroflotation Group, 2009). This application may be called a modified dry bottom feed stone column. For an application, the following procedure is generally followed;

- 1) Prepare geotechnical report for the existing buildings.
- 2) Make a decision on the applicability of this method based on the geotechnical report.
- 3) Obtain the foundation drawing of the existing building.
- 4) Calculate the length, location and the required number of stone columns.
- 5) Produce the stone columns.

To apply stone columns, it requires drilling a borehole through the foundation of an existing damaged building. Boreholes must reach to the bottom of foundation. Then, continuous boring was performed using 60 cm long augers connected to each other until planned length of

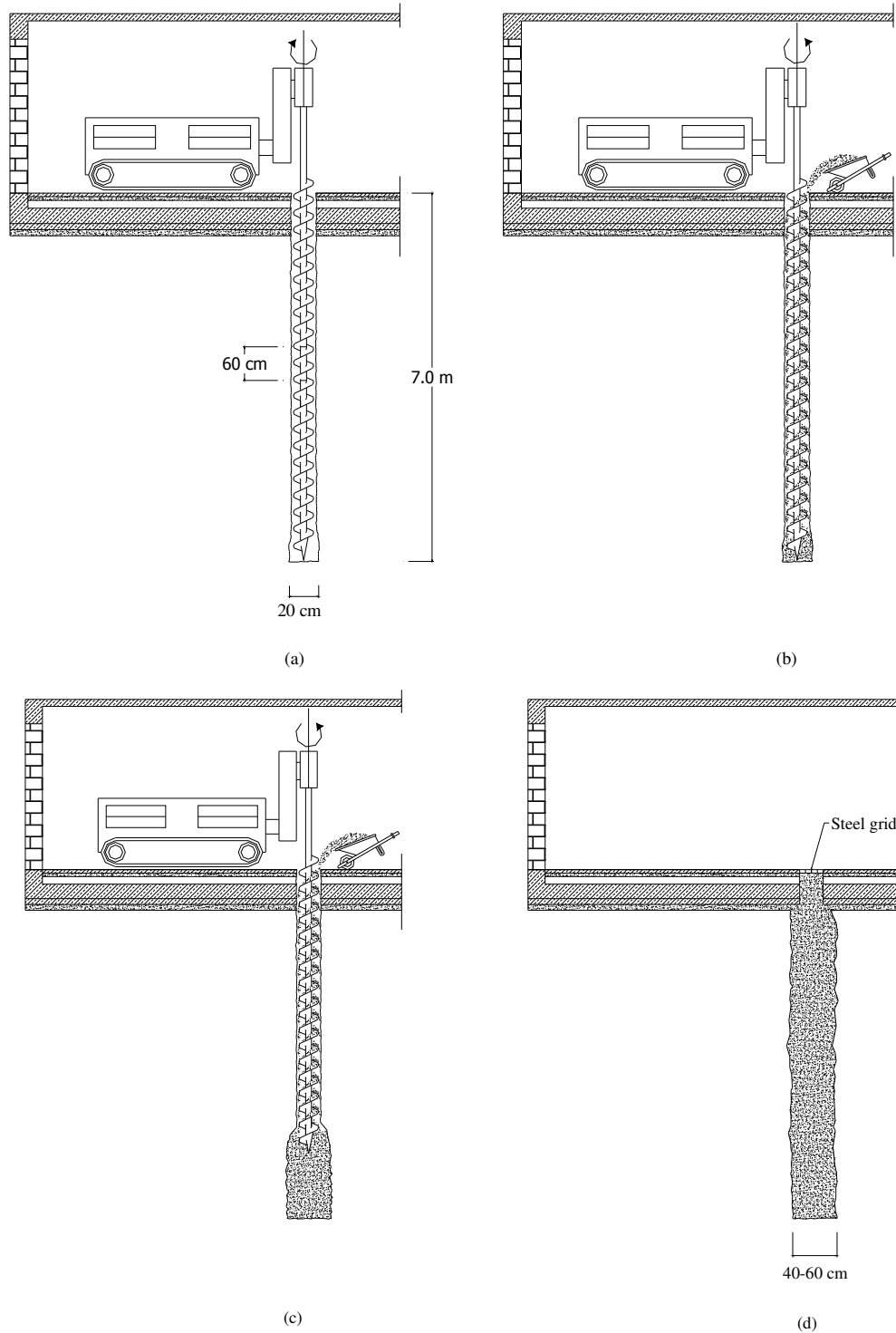


Figure 4. Sequence of stone column application (not in scale).

boreholes for stone column was drilled (Figure 4a). A diameter of boreholes is approximately 20 cm (Figure 4a). Due to limitation of the working space, special design of pile insulation machine with strong torque and reverse auger, which was approximately 20 cm diameter and 60

cm length each, was used. The machine was also capable of applying a hydraulic pressure during an application. Strong torch and hydraulic pressure are transmitted through the crushed stones. This will provide compaction of crushed stones to the bottom and side o

boreholes. Recoil of the machine during the reverse auguring is balanced by a compressive force exerted by the machine. This feature is utilized to apply an extra force during the compaction of crushed stones.

During the preparation of boreholes for stone columns, it was observed that removing of soil from the borehole through auguring was very limited. Boreholes for stone columns were completed both pushing and compacting of soil. Thereby, a maximum compaction can be applied to soil. When the tip of the auger reached to the bottom of a planned stone column, the modified dry bottom feed stone column installation started by reverse turning the auger and continuously pouring crushed stones from ground surface into borehole. Crushed stones go through auger's edges to the bottom and sides of borehole (Figure 4b). A strong reverse torch and hydraulic pressure were continuously applied. When the machine was over loaded, reverse auguring was barely done. In this case, the auguring systems were pulled up approximately 10 - 20 cm and the auguring continued as before (Figure 4c). An insulation process was finished when the top of the stone column was reached. Then, a steel grid was placed on the top of the stone column (Figure 4d). In the modified method, casing of boreholes could not be done due to the operation difficulties in applications. However, the casing has been generally used for the applications, which have no constraints (Datye, 1982).

It is important to keep in mind that the amount of the crushed stone poured in the borehole must be recorded during each operation. A diameter of the stone columns mostly reaches up to 40 - 60 cm, but, it is mainly controlled by geotechnical characteristics of local ground conditions.

Case study: A five-story reinforced concrete building, which was structurally damaged, was selected for a case study (Figure 5).

It was necessary to improve ground conditions and reinforce structural parts of the building. Based on its' geotechnical data, it was decided to use the modified dry bottom feed stone column as a ground improvement method. Figure 6 shows the plan view of the stone columns placed on the foundation and its cross-section. The length of the stone column was decided to be 7.0 m. The amount of crushed stone used for each stone column and the diameter of the stone columns are given in Table 1. The application of the modified method on the site is displayed in Figure 7.

NUMERICAL MODELING AND ANALYSIS

For the presented case study, stone columns in a layered soil were mathematically modeled in order to perform a numerical analysis (Figure 8). Plane stress condition is used in numerical modeling. To assess the effects of stone columns on the constitute model; behavior of the system in computer environment was investigated with



Figure 5. Structurally damaged five-story reinforced concrete building located on liquefiable soil.

Finite Element Method (FEM). FEM was used as a numerical solution method to distinct infinite soil region. The computer code SAP2000, which was suitable for FEM, was utilized in computer modeling.

FEM is a numerical technique utilized to solve problems which were expressed with partial differential equations. Values which are unknown and want to be calculated by FEM are at nodes. When an equation set is acquired for values at size field's nodes using the principle of minimum energy, the equation set in matrix form is typically as follows:

$$[K]\{U\} + [C]\{\dot{U}\} + [M]\{\ddot{U}\} = \{F\} \quad (1)$$

Where; $\{U\}$, which represents unknown values of size field's at nodes, is the element vector, $\{F\}$ is the known element force vector, $[M]$ is the element mass matrix and $[K]$ is the known constants matrix. Also, K is known as stiffness matrix in stress analysis.

In mathematical modeling, horizontal, L_x and vertical, L_y length of distinct soil region were 160 and 50 m, respectively. The modeling was built based on zero displacements along the bottom since the assumption of the distinct system boundary condition at the bottom was bedrock. Horizontal boundaries were also modeled with equivalent static springs and damping.

Calculation of liquefaction potential was indicated that soil under the structure was liquefiable (Table 2). Soil properties used in mathematical modeling is also given in Table 3.

Horizontal and vertical displacements indicate that an average 35% ground improvement is provided through stone column application (Table 4).

Table 1. Amount of crushed stone and diameter of stone columns.

Stone column No:	Stone column length (m)	Volume of crushed stone (m ³)	Diameter of stone column (cm)
SC-1	7.0	1.108	44
SC-2	7.0	1.296	48
SC-3	7.0	1.188	46
SC-4	7.0	1.134	45
SC-5	7.0	1.350	49
SC-6	7.0	1.458	51
SC-7	7.0	1.296	48
SC-8	7.0	1.134	45
SC-9	7.0	1.080	44
SC-10	7.0	1.026	43
SC-11	7.0	1.242	47
SC-12	7.0	1.242	47
SC-13	7.0	1.080	44
SC-14	7.0	1.350	49
SC-15	7.0	1.404	50
SC-16	7.0	1.296	48
SC-17	7.0	1.134	45
SC-18	7.0	1.134	45
SC-19	7.0	1.080	44
SC-21	7.0	1.188	46
SC-22	7.0	1.242	47
SC-23	7.0	1.188	46
SC-24	7.0	1.296	48
SC-25	7.0	1.296	48
SC-26	7.0	1.242	47
SC-27	7.0	1.080	44
SC-28	7.0	1.134	45
SC-29	7.0	1.134	45
SC-30	7.0	1.080	44
SC-31	7.0	1.026	43
SC-32	7.0	1.242	47
SC-33	7.0	1.188	46
SC-34	7.0	1.296	48
SC-35	7.0	1.350	49
SC-36	7.0	1.404	50
SC-37	7.0	1.296	48
SC-38	7.0	1.242	47
SC-39	7.0	1.242	57
Total = 39	Mean Length = 7.0 m	47.466 m ³	Mean Diameter = 47

Especially, it was also determined that ground improvement at and around stone columns were much higher. Away from stone columns, displacements increase.

DISCUSSION AND CONCLUSION

Most of the ground improvement methods available in literature are not directly applicable in Adapazari region

because of the ground conditions under existing damaged buildings. Based on soil data, modified dry bottom feed stone column and reinforced short pile are most applicable in the region. Grouting can only be done in some specific areas in the region, since the region is mainly formed by silty and clayey sand deposits.

There were some difficulties during the modified stone column application. Casing was one of them and could be done during a preparation of boreholes for stone co-

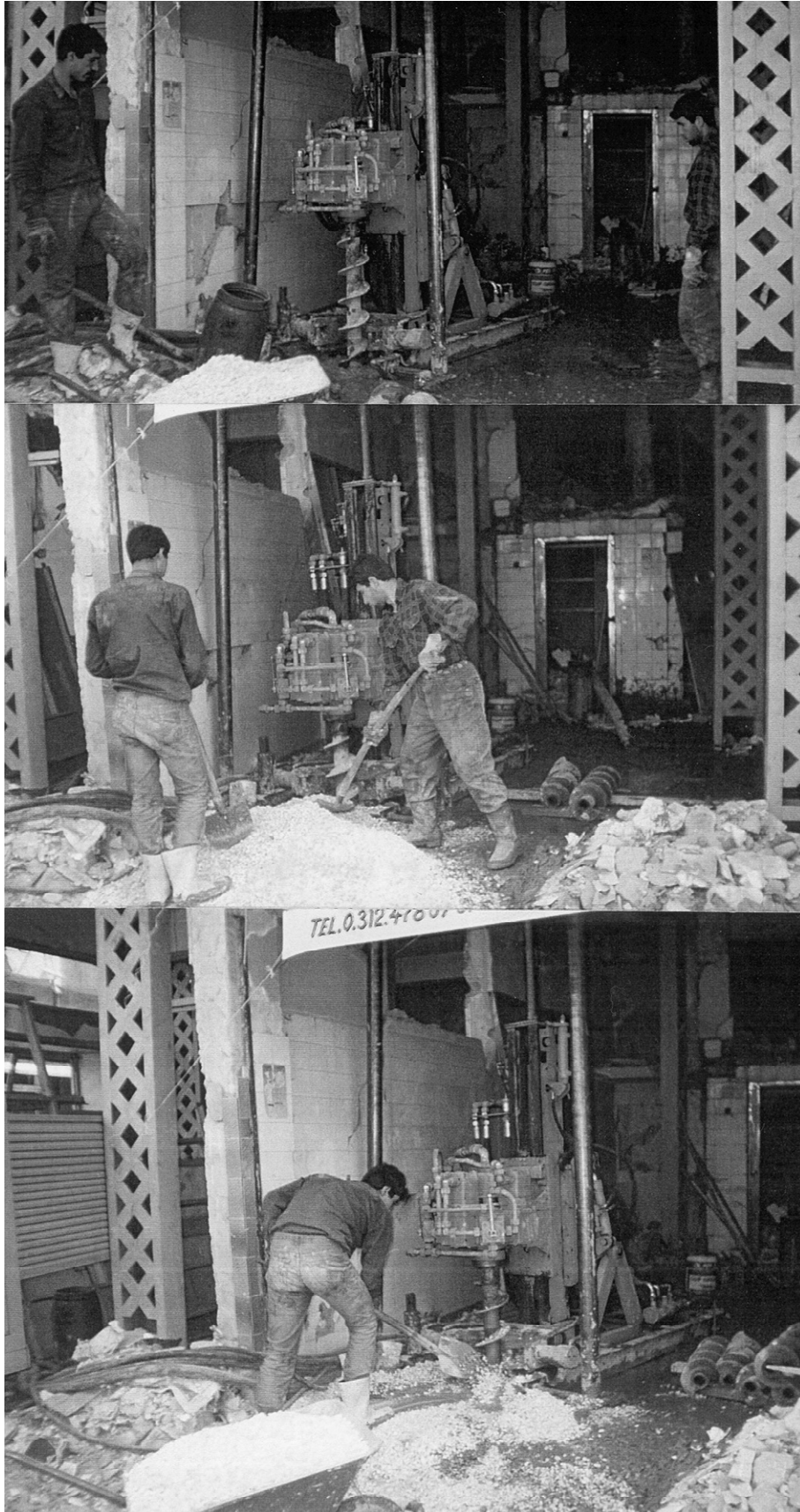


Figure 7. Typical application of stone column.

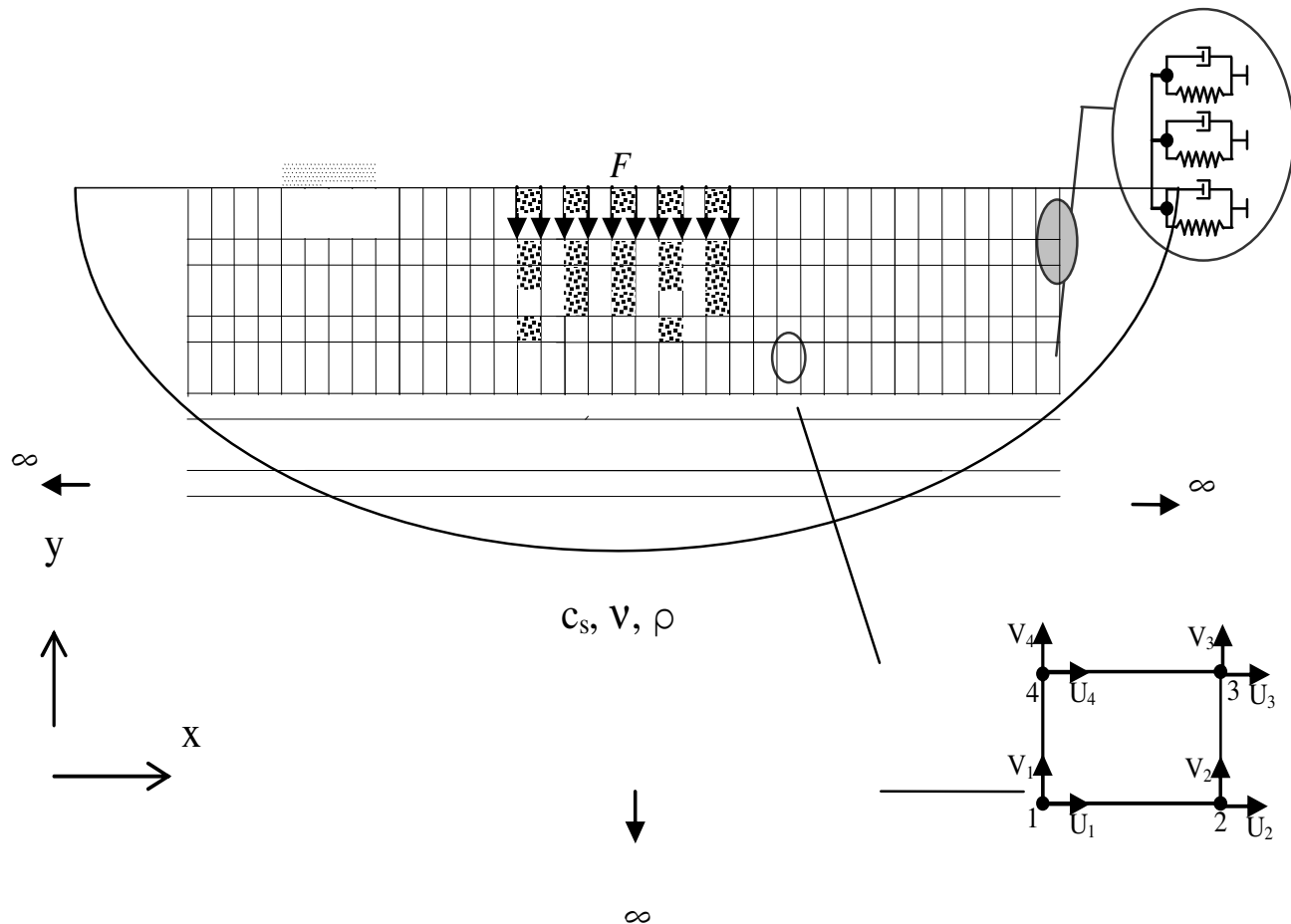


Figure 8. Mathematical model used in numerical analysis.

Table 2. Calculation of liquefaction potential under the structure.

D (m)	r_d	$(N1)_{60}$	CSR_M	CSR_L	σ_{v0}	σ_{v0}'	$\tau_{dev,L}$	τ_{dev}	FS
3	0.98	12	0.14	0.14	94.14	84.33	11.81	24.59	0.48
5	0.97	18	0.20	0.20	130.42	100.99	20.20	33.71	0.60
6	0.96	15	0.16	0.16	148.56	109.32	17.49	38.01	0.46
8	0.94	12	0.14	0.14	184.84	125.98	17.64	46.30	0.38
15	0.77	16	0.18	0.18	315.77	189.24	34.06	64.80	0.53

lumns, concurrently. While pulling up the casing, crushed stone could fill into prepared boreholes, but operation area was extremely limited. Therefore, it was impossible to use casing during the application of modified stone column. To avoid the collapse of the boreholes continuous boring system with reverse auguring was used. During the reverse auguring, crushed stone was filled into the boreholes and compacted. This basically prevents collapse of boreholes during insulations.

The modified stone column is cost effective compared to a reinforced short pile application. Its application is faster than a reinforced short pile. It is a reliable ground improvement technique in terms of its applicability and cost.

On the other hand, there is no quick and proper controlling system for an application of the modified stone column constructed under existing damaged buildings. This could be a disadvantage in its application. The visual

Table 3. Soil properties used in numerical analysis.

Soil	Density ρ (kN/m ³)	Modules of elasticity E (kN/m ²)	Poisson ratio ν (-)	Layer thickness (m)
I. Layer	18.4	20000	0.35	3.0
II. Layer	18.5	20000	0.35	7.0
III. Layer	19.3	30000	0.33	16.0
IV. Layer	20.4	30000	0.33	24.0

Table 4. Displacements at different location under foundation.

Node	Normal case (Before)		Cross-section of A-A (After)		Node	Normal case (Before)		Cross-section of B-B (After)	
	x (mm)	y (mm)	x (mm)	y (mm)		x (mm)	y (mm)	x (mm)	y (mm)
104	99.50	447.30	94.39	297.36	104	99.50	447.30	77.21	199.79
109	86.22	479.42	90.41	326.03	109	86.22	479.42	75.76	220.51
119	67.59	524.88	69.97	368.42	119	67.59	524.88	64.26	273.58
124	55.11	541.95	64.46	403.85	124	55.11	541.95	59.17	313.21
129	43.38	553.01	46.75	415.56	129	43.38	553.01	41.94	327.52
134	31.23	558.48	40.35	402.35	134	31.23	558.48	35.59	315.01
144	14.31	564.73	15.12	410.55	144	14.31	564.73	10.59	322.96
149	2.30	565.72	8.55	431.48	149	2.30	565.72	3.99	342.53
154	9.21	561.65	10.04	428.49	154	9.21	561.65	14.38	336.88
159	21.38	552.38	16.40	401.92	159	21.38	552.38	20.39	306.90
173	39.13	527.80	40.36	381.16	173	39.13	527.80	42.77	273.84
179	51.93	511.45	46.37	388.59	179	51.93	511.45	47.32	248.90
185	64.46	487.18	62.84	369.36	185	64.46	487.18	52.51	224.58
191	77.88	452.93	67.46	325.24	191	77.88	452.93	54.61	203.37
494	2.78	473.59	90.32	314.78	494	92.78	473.59	6.68	209.80
590	1.38	542.87	70.06	377.34	590	61.38	542.87	64.34	284.49
595	37.24	565.08	40.28	400.71	595	37.24	565.08	35.51	313.12
806	8.36	574.52	15.18	412.72	806	8.36	574.52	10.65	324.52
915	15.32	566.35	16.47	406.75	915	15.32	566.35	20.46	313.27
920	45.44	529.16	40.27	376.67	920	45.44	529.16	42.70	264.64
1124	71.14	480.44	67.56	338.22	1124	71.14	480.44	53.79	213.64

inspection and recording of the filled crushed stone can be considered the only way to control the quality of the insulation of stone columns. However, numerical analysis may provide some information to check the suitability and reliability of stone columns. The modeling used in the study proves that modified stone columns provide considerable increase, about 50%, in ground improvement for soils having liquefiable potential. Although the application of the modified stone column has some difficulties, it is expected that liquefaction may be prevented since stone column works as a vertical drain and reduces the pore water pressure during an earthquake.

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