pressure grouting for foundation leveling and soil strengthening. Effectiveness of the proposed remediation plan was then evaluated by comparing the relative settlement of the ground floor slab, before and after the grouting. In addition, comparison on shear wave velocity of the building site, before and after grouting, is also evaluated for the strength improvement of the ground.

FIG. 1 Tilted Building

FIG. 2 Warehouse

SITE RECONNAISSANCE

Based on the standard penetration tests (SPT), the soil profile can be divided into four layers as given in Table 1. In addition to 3m thick of the top backfill layer, the second and the fourth layers contain either silty sand or low plasticity silt. The unified soil classification system was used for soil description given in Table 1. The third layer is 2.6m thick low plasticity clay or silt. Water table is 4.0m below ground surface. The nearest building to the studied building is a one-story steel frame warehouse (FIG. 2), located about 1.9m to 2.8m away from the south side of the inclined building (FIG. 3). The other three sides of the inclined building are open space.

Table 1. Simplified Soil Profile

Layer	Depth(m)	Soil description	N value	Unit Wteight γ_t(kN/m^3)	Water content ω_n (%)
I	0.0~3.0	backfill gravel / sand mixture	9~36(23*)	19.63	10.9
II	3.0~6.8	SM or ML	5~12(8)	19.53	26.7
III	6.8~9.4	ML or CL	7~16(12)	18.53	36.2
IV	9.4~20	SM or ML	11~27(18)	19.53	24.2

*average value

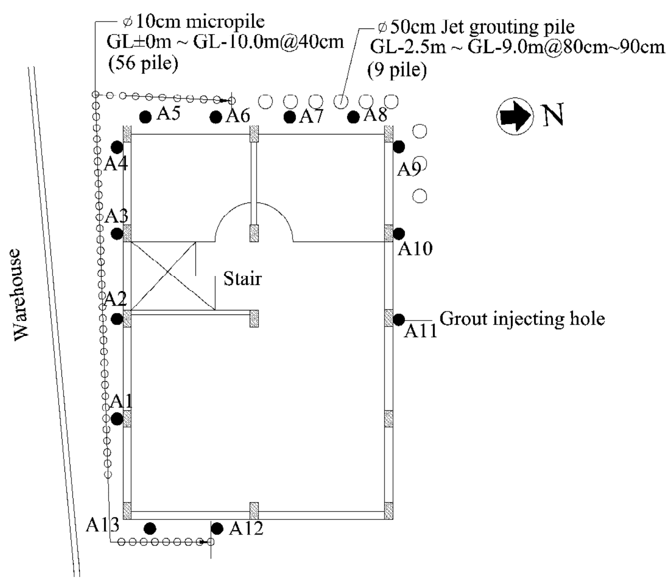

FIG. 3 Layout of micro piles, jet grouting piles and grout holes

During field reconnaissance, it was observed that the building was tilted towards the south-east corner of the building, with angular rotation between 1/110 and 1/150. The foundation of the building is a 25cm thick raft foundation, which is embedded about 150 cm to 200 cm below ground surface (FIG. 4). The maximum differential settlement of the foundation was 17.3 cm. In addition, the maximum differential settlement in the transverse direction of the ground floor slab was 8.1 cm. A PVC water pipe, embedded at 70 cm to 150 cm below ground surface, nearly parallel to the building was observed on the south side of the building. A sewage pipeline, embedded at 30 cm to 50 cm below ground surface, was also observed at the north-west corner of the building.

REMEDIATION VIA GROUTING

The cement grout, injected under the applied grouting pressure of 1961.33 kPa, was used to improve the ground condition of the tilted building. As explained by Hou and Bai (1991), application of cement type grout material in soft clay may work in four different stages which include bulging compaction, flow fracturing, passive earth pressure failure and solid filling. Since the ground condition of the building site includes sandy silt or clayey silt, it is believed that the function of the injected grout will be similar to the description by Hou and Bai (1991). Micro piles and jet grouting were installed first before grouting on the south and west side of the building first as curtain wall (FIG. 3). Purpose of installing the curtain wall is to ensure effectiveness of grouting and to reduce grouting installation effect on the neighboring building. Total fifty-six micro piles, 10cm in diameter and 10m in length, were installed between the tilted house and the warehouse with center-to-center spacing of 40cm. Since no other structure is behind the west side of the building, 9 jet grouting piles, with diameter of 50cm, were installed from depth of 2.5m to 9.0 m. The layout of the curtain wall system is shown in FIG. 3.

FIG. 4 Raft Foundation of the building

Thirteen inclined injection holes were placed, as shown in FIG. 5, for low-pressure cement grouting using single packer. A two-inch (5.08 cm) PVC tube with perforations at every 50cm was used and embedded about 6.5m below ground surface.

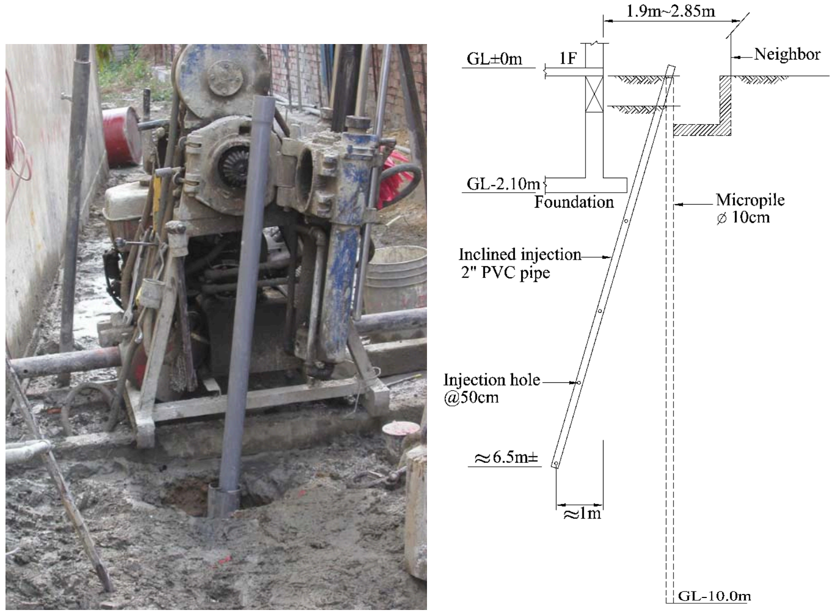

FIG. 5 Layout of instillation of injection pipe

To prevent excessive upheaval of the ground and excessive distortion of the building during grouting, the incremental angular distortion of the building and the maximum uplift of the ground were monitored and controlled within the limits of 1/500 and 2cm, respectively. The grouting process stops once the angular rotation of the building was restored to 1/360. The grouting process started from the south-west corner of the building. The Labile Wasserglas (LW) water glass (sodium silicate) and cement was mixed as the grout material for the project. Portion of the applied grout is each cubic meter of cement grout contains 16 to 18 packs of cement (50 kg/pack) and 0.25 to 0.35 m^3 of sodium silicate. The main constituents of the sodium silicate are given in Table 2. Grouting pressure was maintained around 980.67 to 1961.33 kPa. In addition, the volume rate of grout injection was controlled between 0.02 m^3/min to 0.03 m^3/min. Altogether, it took 15 days to finish the grouting job. 910 packs of cement were used in the project, although 850 packs of cement were considered enough during planning stage based on engineering practice experience. The 28-day compressive strength of the grout was between 1471.5 and 5395.5 kPa. Exerting grout was observed at the ground surface at south-west corner of the building side but not at the warehouse side during grouting. This confirms the effectiveness of the installed micro-pile and jet grouts curtain wall.

PERFPRMANCE OF THE BUILDING AFTER REMEDIATION

FIG. 6 shows the upheaval control monitoring plan. The observed and calculated upheave contours of the ground slab after remediation are shown in FIG. 7, in which the reference point is set at SM1. The maximum differential settlement of the first-floor slab reduces to 2.5 cm after leveling, or 1.4 cm and 1.5 cm in the transverse and in the longitudinal direction, respectively. Comparison on the values of the differential settlement before and after remediation is shown in FIG. 8(a) and 8(b), respectively. In addition, verticality of the building surveyed from front, back and side view before and after grouting lifting is shown in FIG. 9(a) and (b), respectively. The performance of the building proves the effectiveness of the ground improvement scheme.

Table 2. Main Constituents of Water Glass

Specific Gravity	1.29-1.41
SiO2（%）	21-36
Na2O（%）	6-12
Fe（%）	below 0.05
Insoluble（%）	below 0.4

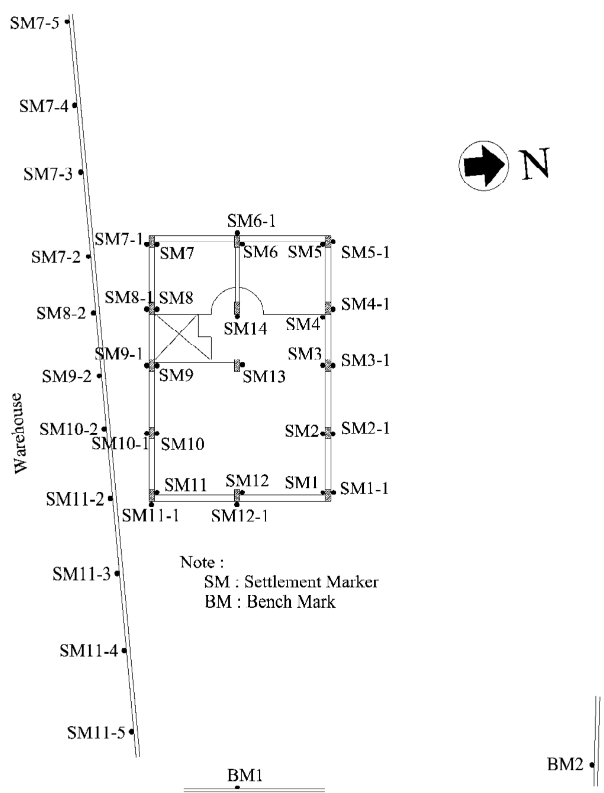

FIG. 6 Upheaval monitoring scheme

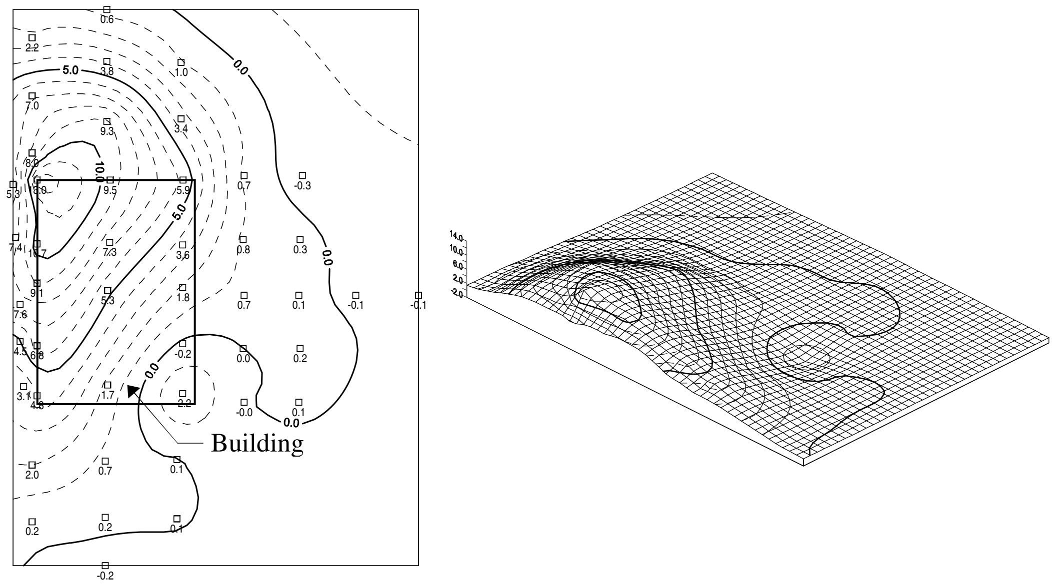

FIG. 7 the contour of upheaval

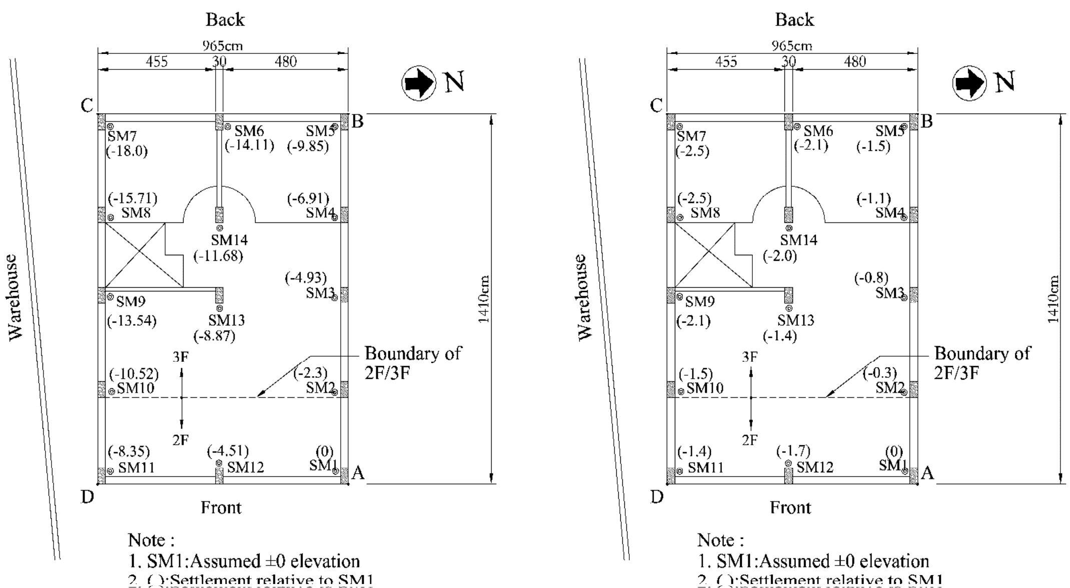

FIG. 8 Settlement of the first floor slab a) before and b) after lifting (Unit : cm)

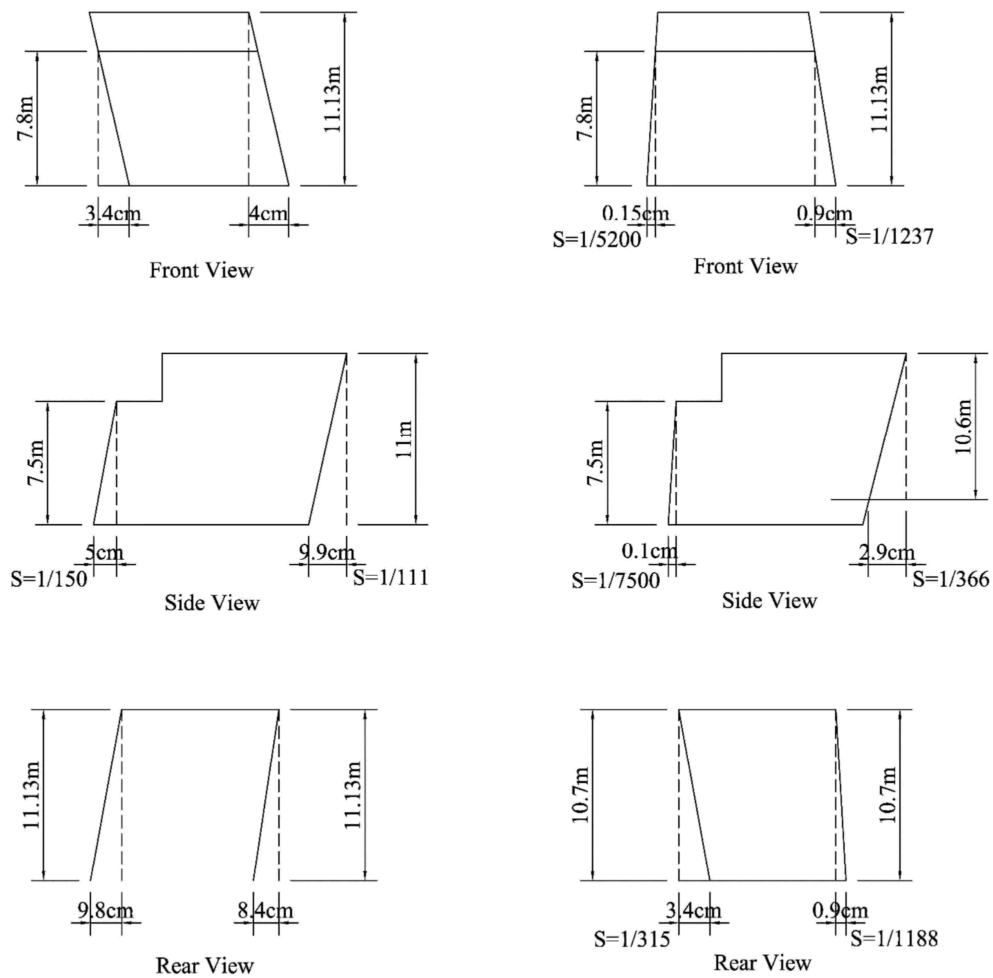

FIG. 9 Verticality of the building (a) before and (a) after lifting

In addition to the performance of the building after remediation, comparison on the shear wave velocity of the ground before and after grouting is also made and is given in Table 3. The shear wave velocity of the ground soil after grouting is 1.5 to 6.5 higher than that before improvement. Apparently, the ground soil strength has been strengthened significantly.

Table 3. Comparison of Shear Velocity before and after Grouting

Before		After	
Depth (m)	Shear wave velocity (m/s)	Depth (m)	Shear wave velocity (m/s)
0.426	176.711	0.543	384.700
0.959	176.747	1.221	391.832
1.625	176.509	2.069	332.951
2.458	176.219	3.129	263.744
3.499	176.043	4.454	337.615
4.800	180.131	6.110	510.493
6.426	184.314	8.180	519.271
8.459	189.513	10.767	694.659
11.000	189.638	14.001	693.732
13.750	189.449	17.501	582.402

SUMMARY AND CONCLUSIONS

Remediation of a tilted three-story building resulted from the earthquake induced soil liquefaction was reported in the paper. The success of the grouting plan was demonstrated by comparing the differential settlement of the ground floor slab of the building, the vertical alignments of the building, and the shear wave velocity of the improved ground before and after the remediation. Some conclusions based on the results of this remediation plan can be drawn as in the following:

1) Comparing to the 17.3cm maximum differential settlement of the foundation before grouting, the maximum differential settlement of the ground floor slab was recovered to 2.5 cm after leveling.

2) The angular rotation, between 1/110 and 1/150, from side view of the building before grouting was improved down to 1/366 and 1/7500, respectively, after remediation.

3) The shear wave velocities of the ground soil remediated by grouting was 1.5 to 6.5 higher than the initial states.

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Grout Everywhere! Multiple Case Studies of Various Grouting Applications in Heavy-Civil Construction Projects

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Abstract

Grout is an engineered material with many practical applications. In fact, the term "grout" doesn't even refer to a single material, but is a general term used to describe many types of flowable materials that are used and handled in many ways to achieve an end result. There are many acceptable ways to mix, transport, and place grout; often multiple ways for each grout formulation. This paper will demonstrate through several case studies some of the ways that grout is used in the engineering and construction of heavy civil projects, particularly its use related to dams and their appurtenances. Selecting various formulations of cementitious and chemical grouts, when one may be preferred over the other, and how the grout's material properties can be modified to produce the desired results will be discussed. Case studies will include the use of low viscosity urethane grout used to fill cracks in the face of a dam and use of higher viscosity urethane grout to install a seepage cutoff curtain behind the conventional concrete face of a roller compacted concrete (RCC) dam that was partially lined with a geosynthetic liner. This same project used urethane grout as the preferred alternative to grout the annular space around three drain pipes that were cored through the RCC dam, the selection of which was based solely on the limited mobility properties of the urethane grout formulation as opposed to the higher mobility potential of cementitious grout, which could clog drains installed within the RCC dam body. Other case studies will discuss the use of cementitious grout, with and without aggregate, which was used to fill the annular space after existing outlet tunnels at two dams were lined with steel pipe. Different means and methods were used to place the grout because of differing access conditions. The use of grout socks to contain cementitious grout for foundation anchors installed in Karst bedrock beneath a spillway chute will also be discussed to demonstrate the importance of geologic considerations during project design and construction. A case study on abandoning old pipes through embankments will be discussed, including the use of multiple grout injection and vent pipes to successfully fill the abandoned pipes, and bulkhead construction techniques used to contain the grout at the ends of the pipes will be discussed. Reflections on 25 years of experience on various grouting projects and lessons learned will be included.

INTRODUCTION

The term grouting means different things to different people, depending on their experience and area of practice. Grouting has many practical and even essential applications in heavy civil engineering projects, most of which are beyond the scope of this paper, which focuses on a few