Application of Computed Tomography technology for exploration of deep underground cavities and solution features

S.L. Chiu, T.S. Lam & Harry W.P. Yu
Maunsell Geotechnical Services Limited, Hong Kong

ABSTRACT
This paper presents a case of the application of Computed Tomography (CT) technology on detection of underground solution features and cavities for a commercial development site in WuXi, People Republic of China. Three high-rise commercial buildings of height 340m, 155m and 90m respectively, with a basement of 20m deep were proposed to be constructed. From the results of preliminary and detailed ground investigation, it was revealed that the rock head was about 85m below ground. However, solution features and cavities of various sizes were present in the first 60m below the rock head level. Such solution features and cavities are vulnerable and prone to collapse when subjected to the imposed building loads.

In order to delineate the spatial locations and sizes of these solution features and cavities probably present in bedrock under the footprints of the proposed buildings, two different geophysical surveys, namely Seismic Wave CT method and Electromagnetic Wave CT method, were carried out on site. With the aid of computed tomography technology, the large amount of spatial survey data were woven together to make images of the underground anomalies, and hence provided information on their locations and sizes for foundation design engineer to get over this complex foundation problem.

Keywords : computed tomography ; solution features ; ground treatment ; CT imaging

1 INTRODUCTION

The proposed commercial development was situated in WuXi, a beautiful lakeside city in the eastern part of China. Three towers of commercial buildings with 3 to 4 levels of basement and 2 levels of podium structure were to be built on the site of size 29160 m^2. In the preliminary design, the proposed main tower was 340m above ground and the remaining two towers are 155m and 90m respectively, and the depth of proposed basement was 20m below ground. According to the estimated loadings, deep foundation with piles of founding level 80m below ground was adopted.

Preliminary ground investigation was carried out in early 2007. 13 bored holes of depth from 90m to 120m were sunk for collecting subsurface information for the preliminary foundation design. It was found that in about top 20 m of the bedrock there were solution features developed to various degrees, with heights ranging from 0.10m to 1.6m and 0.68m in average. Most of the voids were filled with yellowish-brown, stiff clay with rock fragments. Thus, it was considered that the solution features were inactive. Otherwise, the bedrock were described as intact and classified as moderately strong to strong Grade II limestone.

Detailed ground investigation commenced in late 2007. 57 additional bored holes were sunk with a maximum depth up to 150m below ground. As reported by the contractor, there were cases of loss of drilling slurry and sudden drops of drilling rods in the course of ground investigation into the limestone bedrock. Inspection of the core samples confirmed the presence of solution features with height ranging from 0.1m to 6.1m. Most of them were filled by brownish red silty clay with limestone and calcite fragments. Some of them were partially filled or empty. RQD ranges from 35% to 80%. Limestone between solution features was moderately strong, moderately fractured and moderately decomposed. The solution features were generally filled with cementous calcite and partially filled with clayey soil.

Since the founding level of the proposed foundation bored piles was very close to the locations of the solution features, the solution features were prone to collapse when subjected to the imposed building loads transferred from the foundation piles. To avoid this, the solution features and cavities had to be filled such that the loadings can be evenly spread and minimize stress concentration at the rock column between cavities. Before any treatment to the solution features, the sizes and locations of the solution features had to be identified. In addition to the traditional ground investigation boreholes geophysics survey using computed tomography was proposed to explore the underground solution features.

2 COMPUTED TOMOGRAPHY TECHNOLOGY

2.1 *Brief Introduction of Computed Tomography Technology*

Computed Tomography (CT) technology has been applied in medical sciences for years. The inter-borehole electromagnetic wave CT was first adopted in geophysics.

Computed Tomography is a technique in which an incident beam of signal, such as seismic or seismic wave, electricity current, electromagnetic radiation (x-rays or gamma rays) passes thought an object and is collected with an array of detectors (Alshibli et al, 2000). The word “tomography” is derived from the Greek *tomos* (slice) and *graphein* (to write). The attenuation information collected is then read by a computer program to reconstruct a slice image of the internal structure of objects. Three-dimensional reconstructions can be made by stacking the CT slices and attenuation is measured on individual planes whereas conventional radiographs comprise attenuation data from all planes within an object superimposed onto one plane.”

Dines et al (1979) carried out an experiment on an urban mass-transit site for testing the attenuation reconstruction of data for electromagnetic and seismic wave in straight-wave cross-borehole probing. It was concluded that data from both electromagnetic and seismic wave could also be used to reconstruct the structure of the object being passed through.

Fonseca et al (2005) made use of P and S-wave seismic refraction and reflection data in cross-holes or down-hole

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method in an experimental site to form tomography section to investigate /characterize the sub-soil profile and formulate the preliminary geological interpretation model for determination of the relevant geotechnical properties of the sub-soil profile.

Lee et al (2000) also carried out borehole geophysics in ground investigation for foundation design in limestone rock area. A combined natural gamma and induction probe was used to obtain information on the karst features whereas ground penetration radar was used in cross-hole for further exploration in the areas within complex karst features. The results revealed that it was a useful tool for foundation design in karstic environment and hence significantly reduce total number of deep holes for the design of deep foundation.

3 RESULTS OF TOMOGRAPHY IMAGING

3.1 *Designed Geophysics Survey using Computed Tomography Technology*

The missions of this geophysics survey were as follows:-

a. To create imaging of electromagnetic-wave and seismic-wave geophysics surveys for every cross-section in order to visualize the locations, sizes and other information regarding the solution features and fissure zones.

b. To create imaging of electromagnetic-wave and seismic-wave geophysics surveys on plan at each metre depth (from rockhead level to -150mPD) in order to visualize the locations, sizes and other information regarding the solution features and fissure zones.

c. To calculate the areas of the solution features at each cross-section and thus estimate the volume of solution features and cavities to be treated.

Two different forms of computed tomography, namely seismic wave and electromagnetic wave CT methods, were adopted in this geophysics survey. The geophysics survey was confined within the footprints of the three towers with heavy building loads. Bored holes of maximum depth 150m with steel casing were drilled into the ground for allowing the passage of the signal generators and receivers to reach the bedrock layer. The amount of works carried out for the geophysics survey is tabulated as follows:-

Tower	Drillhole		Number of GS Cross-Sections for both Electromagnetic and Seismic Wave CT
	Quantities	Depth	
1	17	150	34
2	13	150	24
3	13	150	24

3.2 *Results of CT Imaging of the Site*

The geophysics survey identified two types of the solution features, which are solution features (void or incompletely infilled) or fissure zones (completely infilled or of size less than 0.6m in diameter). Figures 1 and 3 show the cross-sectional and plan imaging of the geophysics survey at Tower 1 using seismic wave CT method, while Figures 2 and 4 show the cross-sectional and plan imaging of the geophysics survey at Tower 1 using electromagnetic wave CT method at the same locations.

The results showed that the solution features were mainly distributed at levels between -81mPD and -110mPD, especially within levels between -81mPD and -100mPD. The solution features were located at different levels and inter-connected. The fissure zone in bedrock also existed in these depths. Scattered solution features were also present in rock at levels about -130mPD.

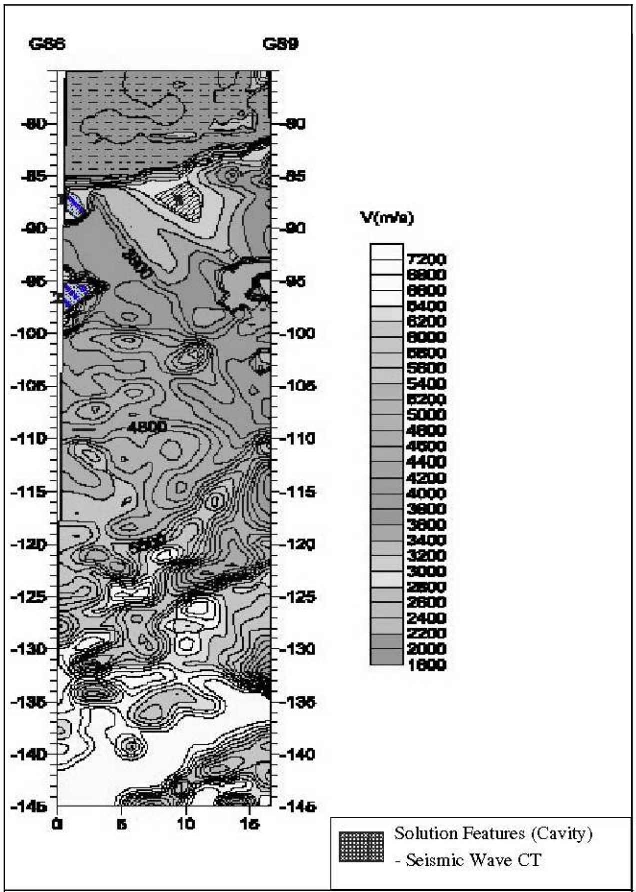

Figure 1. Cross-Sectional Imaging of Seismic Wave CT Method between 2 boreholes at Tower 1

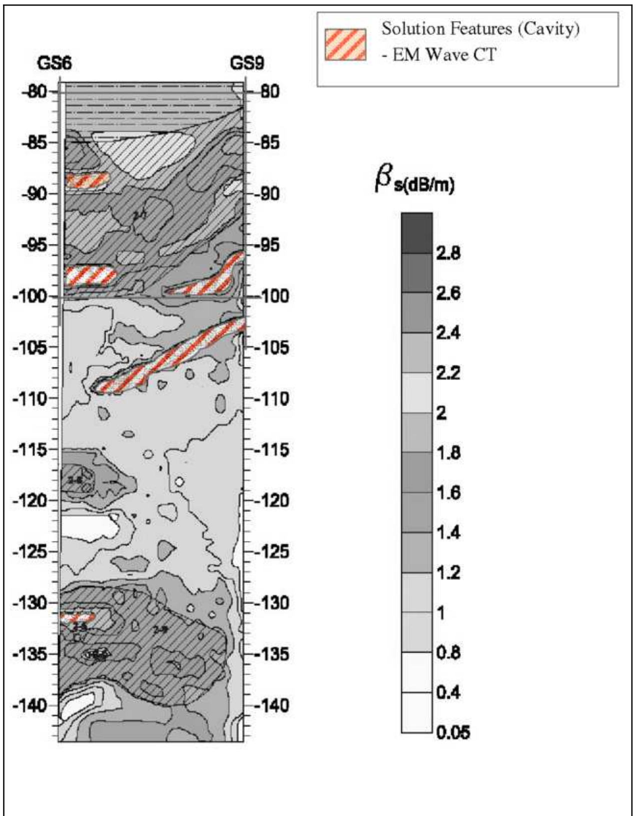

Figure 2. Cross-Sectional Imaging of Electromagnetic (EM) Wave CT Method between 2 boreholes at Tower

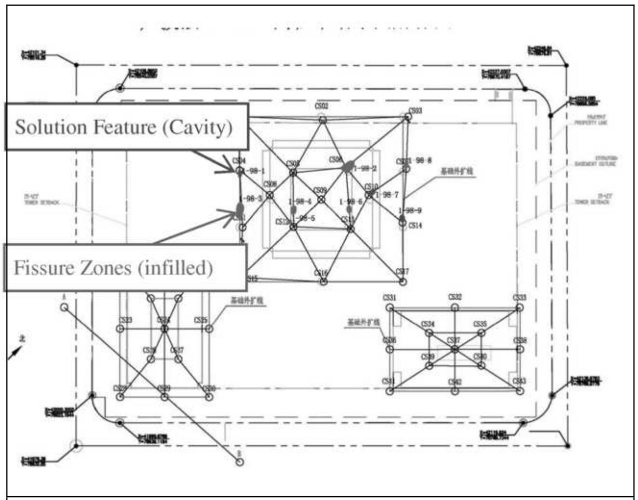

Figure 3. Plan Imaging of Seismic Wave CT Method of Tower 1 at Level -98mPD

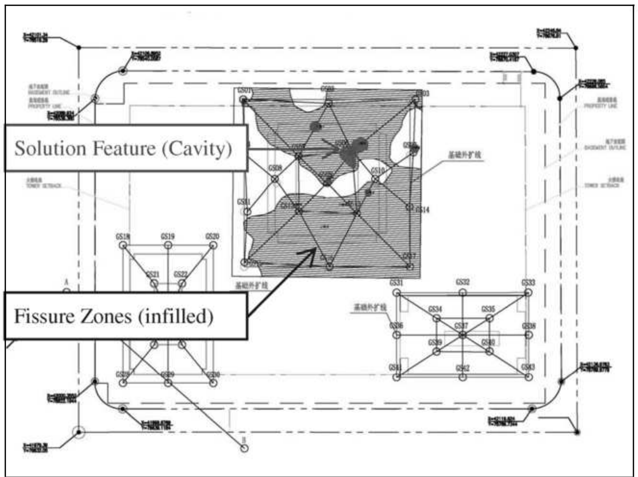

Figure 4. Plan Imaging of Electromagnetic Wave CT Method of Tower 1 at Level -98mPD

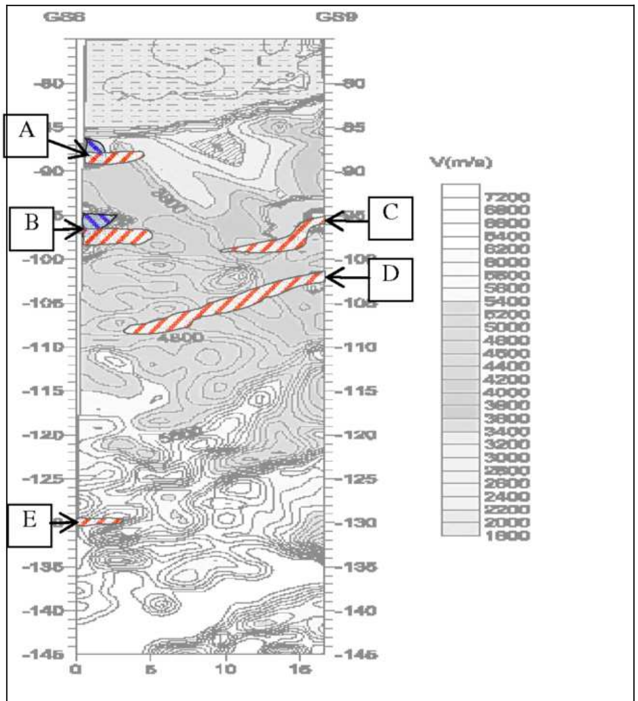

Figure 5. Comparison of Results of EM-Wave and Seismic-Wave CT Methods

3.3 *Verification of the Results of CT Imaging*

- Verification by GI boreholes

The locations of solution features and fissure zones were further verified with the core samples obtained in the detailed ground investigation. At the top 30m of the bedrock, the findings from geophysics survey generally matched with the rock cores extracted from the boreholes in detailed ground investigation. At depths where solution features (cavities) identified in the geophysics survey, wash bore or rock with low RQD values were obtained in detailed GI. At depths where fissure zones identified in the geophysics survey, cores filled with brownish red stiff clay with rock fragment were obtained in detailed GI. However, at greater depth of the bedrock, the correlation between findings in geophysics survey and rock cores in detailed GI reduced.

- Comparison of 2 different geophysics survey methods

Figure 5 shows the cross-sectional imaging results using Seismic Wave CT method, and the locations of solution features identified using Electromagnetic Wave CT method (in red) and using Seismic Wave CT method (in blue) are overlaid for comparison. It can be observed that at Points A and B in Figure 5, both CT methods identified solution features at approximately the same locations. At Points C, D and E, however, solution features can only be identified in the Electromagnetic Wave CT geophysics survey. Moreover, the extent of fissure zones identified by using electromagnetic wave CT method was much larger than that identified by using seismic wave CT method.

The discrepancies of the results may be explained by the difference in the measuring principles of the two CT methods of geophysics survey. For electromagnetic wave CT method, it measures the conductivity of electromagnetic waves of the medium between the two boreholes. Medium with abnormally high conductivity for EM wave at particular locations in bedrock will be treated as the possible presence of solution features. For seismic wave CT method, it measures the time of travel and the change in energy of the seismic wave from one borehole to another. As the two methods measured different qualities for the classification of solution features and fissure zones, the extents and locations identified using these two methods were not identical.

4 PROPOSED REMEDIAL WORKS FOR THE BEDROCK WITH SOLUTION FEATURES

In view of the characteristics of the solution features in bedrock at Tower 1, it is suggested that the piled foundation be rested on the soil stratum. If piles on the soil stratum cannot fulfill the requirements on the settlements and loading capacities and hence the piles have to be founded in bedrock, grouting shall be carried out at the solution features and fissure zone in the bedrock stratum. Based on the estimated loadings from the towers, pile length of 60m was designed and the spreading of tower loading at the foundation is illustrated in Figure 6.

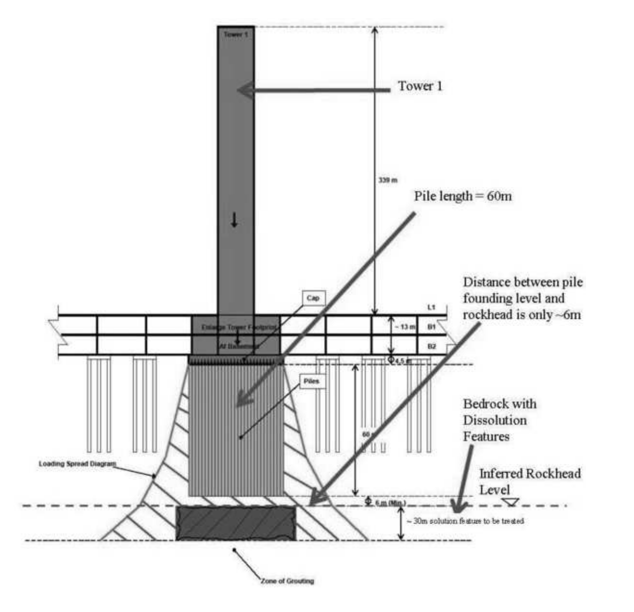

Figure 6. Simplified Load Spread Diagram of Tower 1

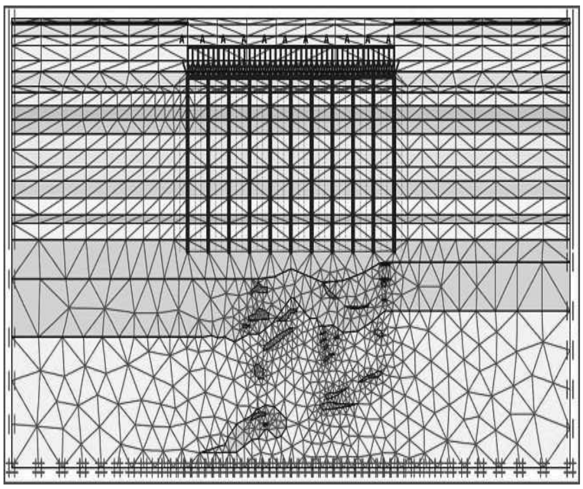

Figure 7. Stress Analysis of the Bedrock with Solution Features using Computer Programme "Plaxis" for Tower 1

Detailed analyses of foundation and rock mass behaviour were carried out using finite element computer programme "Plaxis v8.2". Two-dimensional stress analyses of the bedrock adjacent to the solution features and cavities were carried out to determine if there is any overstress at the pinnacles in between cavities and at the top of cavities before any ground treatment at the bedrock. The analytical results demonstrated that at particular locations between cavities, the additional stresses exceeded the limit bearing capacity.

The computer model was then adjusted by increasing the values of Young Modulus of the material inside the solution features to simulate the effects after cement grouting carried out at the first 30m below the rockhead. The results showed that at locations where additional stresses exceeded limit in the previous case, the additional stresses could be decreased by 65% and thus within the allowable bearing pressure of rock.

The analyses demonstrated that the proposed treatment to the top 30m of the bedrock was sufficient and could significantly improve the bearing capacity of the bedrock below the foundation of the tower.

5 CONCLUSIONS

Computed Tomography Technology provides a cost and time effective way in the visualization of the subsurface conditions and the exploration of the karsts and solution features. The case presented in this paper provides another example of the application of computed tomography technology in exploration of deep cavities and solution features at depths more than 80m below ground. Foundation engineers can make use of this technology to have a better understanding of the distribution of anomalies underground.

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