Kim, J.-H., Yi, M.-J., Hwang, S.-H., Song, Y., Cho, S.-J., Lee, S.-K., Application of integrated geophysical methods to investigate the cause of ground subsidence of the highly civilized area.
International Symposium on the Fusion Technology of Geosystem Engineering, Rock Engineering and Geophysical Exploration
Seoul, Korea, Nov. 18-19, 2003

Application of integrated geophysical methods to investigate the cause of ground subsidence of the highly civilized area

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Abstract: Ground subsidence has occurred in the downtown of Muan-eup in Korea. Integrated geophysical survey, including two-dimensional resistivity, CSMT(Controlled source magnetotelluric), magnetic, borehole logging, GPR and resistivity tomography, has been conducted to investigate the cause of subsidence and ground conditions. Since the target area is in the city downtown, there were no spaces for surface geophysical methods. To get regional geology and to facilitate the detailed geophysical interpretation in the survey area, two-dimensional resistivity, CSMT and magnetic surveys have been applied in the outer region of the downtown. From these results, we could accurately define the Gwangju fault system and estimate the geologic conditions in the downtown. For the detailed survey of the downtown area, resistivity tomography and borehole logging data have been acquired using a few tens of densely located boreholes. Among these survey results, borehole logging data provided the guide to classification of the rock type and we could define the geologic boundary of granite and limestone formations. From the resistivity tomograms of 42 sections, which are densely located enough to be interpreted in a three-dimensional manner, we could delineate the possible weak zones or cavities in the limestone formations. In particular, resistivity tomograms in the subsided area showed the real image of ground subsidence. The map of hazardous zone has been derived from the joint interpretation of these survey results and we could provide the possible reinforcement strategy in this area.

1. Introduction

An integrated investigation was conducted to estimate the ground stability at Muan-eup, a small city located at the south-western end of Korean Peninsula. We applied geophysical exploration to image the underground structure as well as rock engineering investigation to estimate the ground condition. In the survey area, especially in the downtown, there has occurred a series of events issuing a serious question on the ground stability such as ground subsidence, and ground cave-in (Fig. 1), since 1990's. The purposes of investigations were to examine the cause of subsidence, to locate the unstable area in the downtown, and finally to provide the possible reinforcement methods. This paper focuses the results of geophysical investigation.

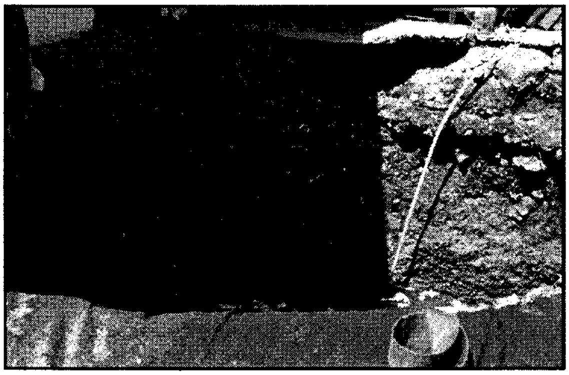


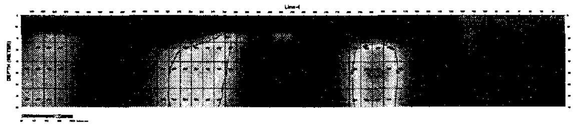
Fig. 1. An example of ground cave-in occurred at the survey area.

By the preliminary survey, it was found that limestone develops under Muan-eup area, and moreover cavities are formed in limestone. Therefore, it would become the most important task to locate limestone cavities. It would be also important to delineate fractures and geological lineaments as the path of ground water flow in which cavities are liable to develop (Kim et al., 2003). To do these, an integrated geophysical survey was performed including dc resistivity, CSMT(Controlled source magnetotelluric), magnetic, GPR(Ground penetrating radar), geophysical well logging and crosshole dc resistivity tomography. Since the main target area is in the downtown where all the roads are paved and buildings stand close together, it is nearly impossible to apply surface geophysical methods to investigate geological structure in detail. To overcome this problem, we applied dc resistivity, CSMT and magnetic methods to outside region of downtown, instead to apply them directly to the main target area. And we attempted to get the accurate geological setting of the whole area by combining the surface geophysical results from the outside region of downtown and the detailed survey results form the inside. For the detailed survey in the downtown, 37 boreholes were drilled, and geophysical logging was carried out for entire wells. Crosshole resistivity tomography over 42 tomographic sections was performed to image limestone cavities precisely throughout the whole target area, which was the most important goal of geophysical investigation.

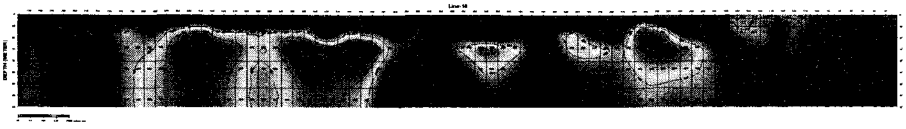
2. Regional geological structure- results of surface geophysical survey outside the city center

Surface geophysical surveys were conducted separately at the north-eastern and south-western area outside downtown and include 7 km of dc resistivity, 5 km of magnetic and 3 km of CSMT surveys (see Fig. 3). CSMT survey was to delineate the deeply extended fracture zones and lineaments, dc resistivity to get the images of shallow subsurface while the purpose of magnetic survey was to get the information of lineaments and geologic boundaries. A major fault in Southwestern part of Korea, Gwangju fault runs though the eastern margin of the survey area as shown in Fig 3. Furthermore, pre-Mesozoic limestones and schists were intruded by granite and rhyolite and there happened many subsequent tectonic activities, to make the geologic setting so complicated.

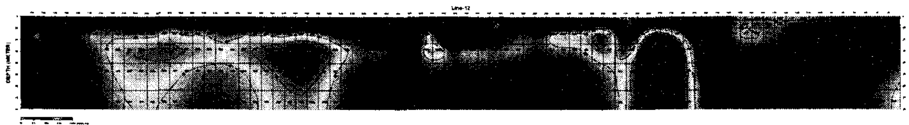
Fig. 2 shows the subsurface resistivity distribution images as the results of the inversion of the dc resistivity survey data along the mutually parallel three lines. All the three images show wide low resistivity zone at the eastern part corresponding to fracture zones associated with Gwangju fault. Vertically extended low resistivity zones at the middle parts of the images appear as mutually connected, which indicates that fractures in limestone are elongated.



(a) RES-4



(b) RES-10



(c) RES-12

Fig. 2. Inverted dc resistivity images acquired at the north-eastern part of the survey area.

Fig. 3 shows the overall geology interpretation combining the surface geophysical results and known geology. We can clearly see Gwangju fault running through the area with declination of N35°E, which appears to be slightly dislocated to eastern direction in geophysical results when comparing geologic map. Note also that weak zones are widely distributed in granite region at the western part.

Distribution of limestone is probably the most critical point regarding the subsidence and Fig. 3 shows the characteristic wedge-shaped feature of limestone in this area. Several fractures and weak zones are developed toward the downtown in this limestone, which correspond to the central low resistivity zones in Fig. 2. Weak zone and fractures may serve as good conduits of groundwater and thus cavities are likely to develop along these weak or fracture zones. On the other hand, tuff or rhyolite and granite around the limestone may confine the groundwater flow in limestone, and thus the wedge shape of limestone can help the groundwater flow concentrating on downtown area. Therefore, we can say that there are much more cavities in downtown than outside, which is the main cause of subsidence and sinking phenomena happened about more than 10 times in 1990's along with the excessive pumping of groundwater.

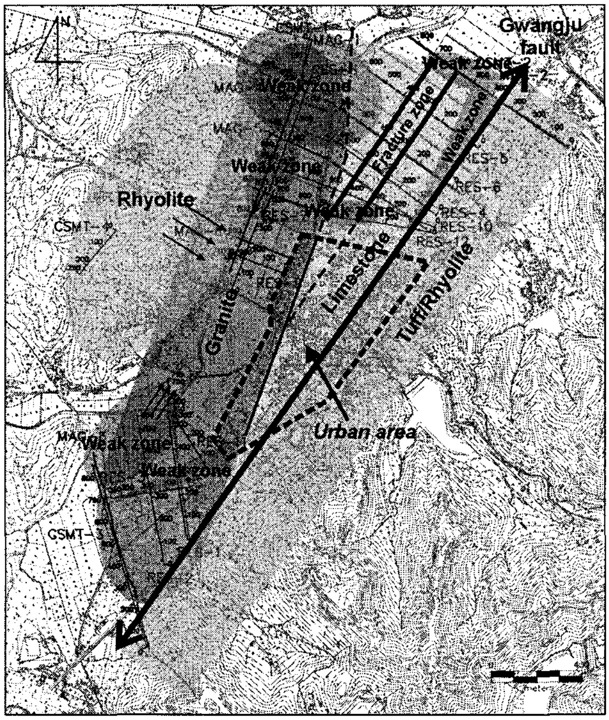
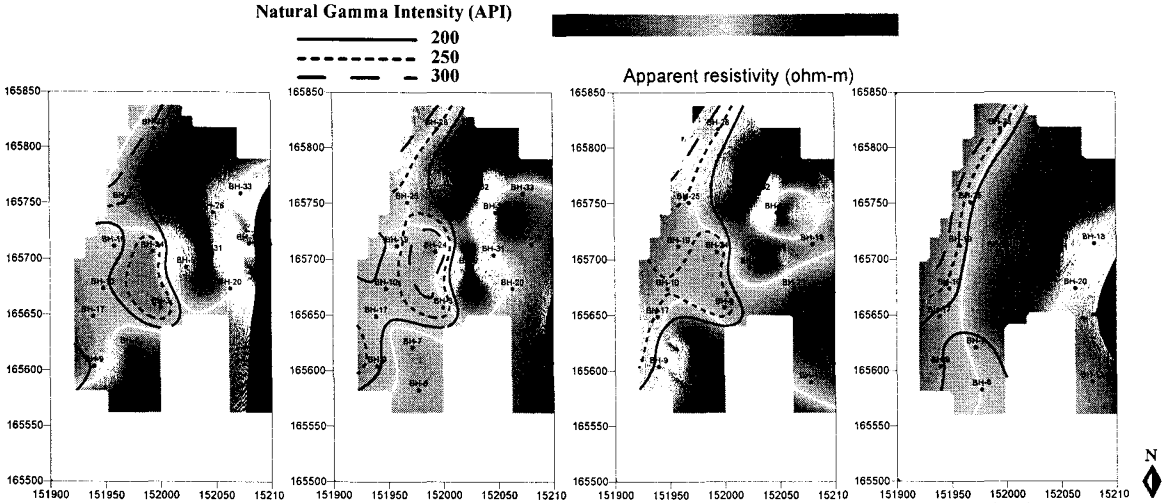


Fig. 3. Interpreted geological structure surrounding the downtown area through surface geophysical surveys.

3. Distribution of limestone and granite at the urban area- results of geophysical logging

Although ground subsidence has occurred within the limestone area, the locations of ground subsidence are mostly concentrated along the boundary between granite and limestone, rather than that between limestone and tuff/rhyolite. Therefore, it would be meaningful to delineate the boundary between granite and limestone in three dimensional manner. Examining the geophysical logging data carefully, it was turned out that granite and limestone can be discriminated by resistivity and natural gamma intensity. Normal logs show that the resistivity of granite in this area is near or below 1,000 ohm-m, while that of limestone is higher in general. And the natural gamma intensity of limestone is less than that of granite (Hearst, et al., 2000).

For the interpretation of the horizontal and vertical extent of limestone and granite, we examine the horizontal distribution of apparent resistivity and natural gamma intensity at each depth using the well logging data from 19 boreholes in and around the subsided area. Considering the characteristics of well logging data, 200 API has been assigned to the black solid line, and 1,000 ohm-m to white solid line in Fig. 4. Granite and limestone can be discriminated by these two values of natural gamma intensity and apparent resistivity. The overall trend of 200 API line shows NNE-SSW direction, and·agrees with the result of surface geophysical survey in Fig. 3. Since the extensions of limestone boundaries predicted by surface geophysics show a good agreement with those confirmed by core drillings, we describe the boundaries in Fig. 3 as thick lines although surface geophysical surveys were not applied in the downtown. However, the distribution of natural gamma intensity and apparent resistivity in Fig. 4 changes with depth, which implies the intrusion of granite of western side into limestone of eastern side. In Fig. 4 (a) of 15 m depth, a part of 200 API contour line is elongated in the direction of SSE, which means that the granite intrusion starts southwards at about 15 m depth. In Fig. 4 (b) and (c), we can notice that the granite intrusion occurred extensively at the depth of 20 and 30 m. The isolated low resistivity anomaly around the borehole BH-25 represents the cavity detected by the drilling. At 40 m depth, the 200 API and 1,000 ohm-m contour lines become simplified and show the regional trend of NNE-SSW direction, which implies that the granite intrusion from western side occurred at the upper part only.

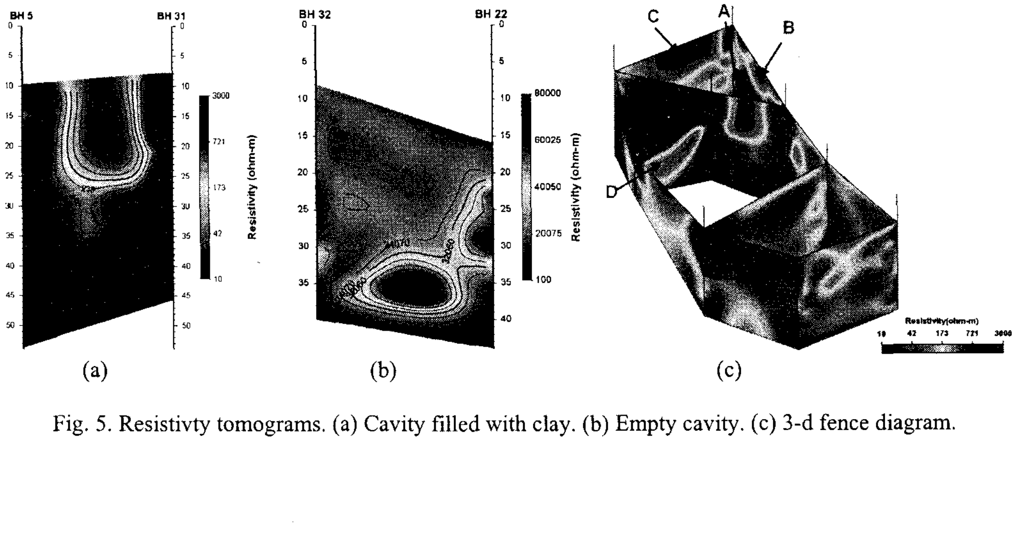


(a) depth : 15 m (b) depth : 20 m (c) depth : 30 m (d) depth : 40 m

Fig. 4. Horizontal distributions of natural gamma intensity and apparent resistivity from geophysical well logging around the city downtown where ground subsidence has taken place several times. Black solid and dotted contour lines are for natural gamma intensity, and white solid lines correspond to the resistivity of 1,000 ohm-m.

4. Images of limestone cavities at the downtown- results of resistivity tomography surveys

To image the cavities and weak zones developing under the main target area, crosshole resistivity tomography has been applied over 42 tomographic sections, which are formed by 24 boreholes as shown in Fig. 6. Applying tomography survey to such a many sections was mainly motivated to locate the cavities and weak zones accurately throughout the whole target area. It was also inevitable to get the underground images over the whole target area, because of the lack of space for surface geophysical surveys due to buildings, roads and heavy traffic. We applied GPR method naturally, which was believed to be the most applicable in this situation, but we could not get meaningful images since the maximum depth of investigation was merely less than 10 m even when adopting 50 MHz antenna.

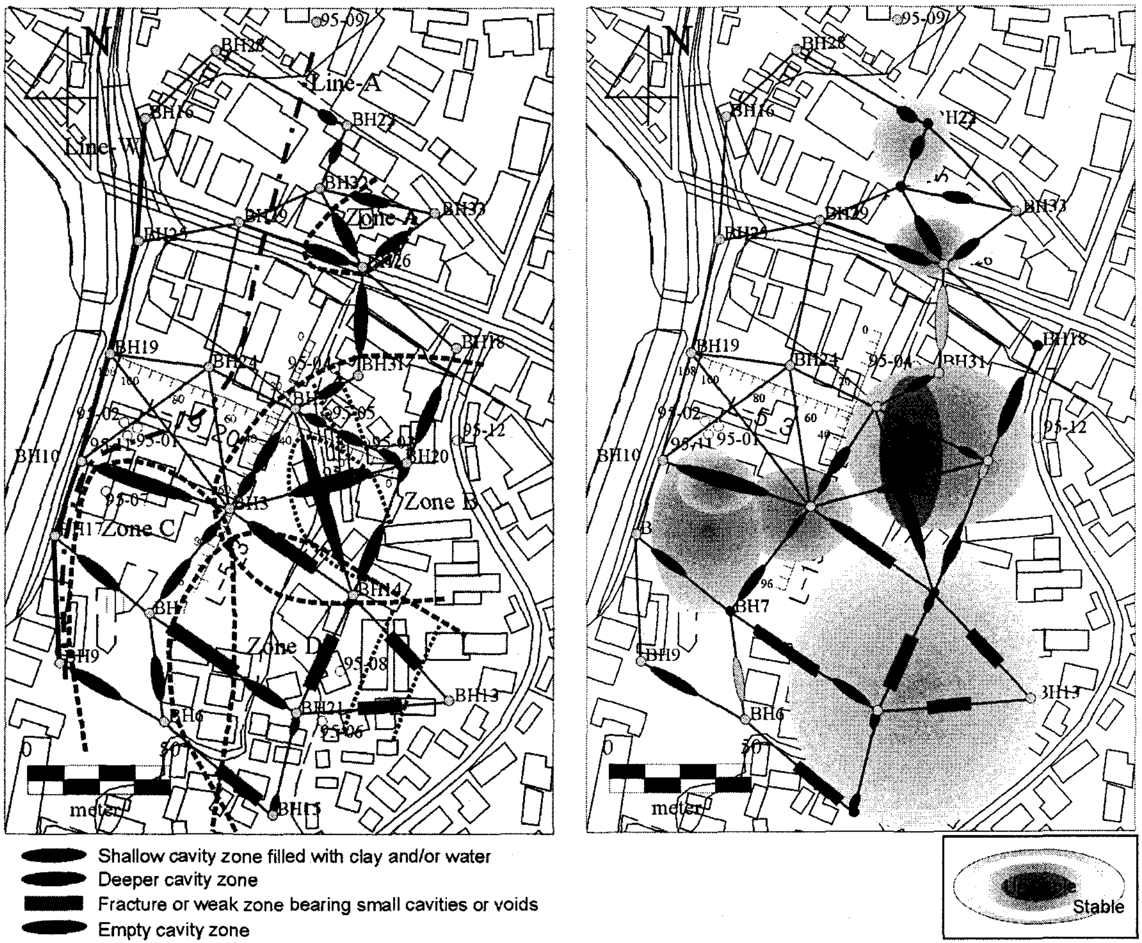


(a) (b) (c)

Fig. 5. Resistivty tomograms. (a) Cavity filled with clay. (b) Empty cavity. (c) 3-d fence diagram.

Fig. 5(a) shows a typical example of resistivity tomogram that clay-filled cavity is clearly imaged. The cavity corresponds to the low resistivity anomaly extending down to the depth of 20 m. This image was acquired at the ground subsidence area of Fig. 1 just after temporary restoration work, and the vertical dimension of anomaly coincides with the amount of ground subsidence, which was reported to be 20 m. Contrary to these cavities, Fig. 5(b) shows an empty cavity, which is imaged as a high resistivity anomaly in the figure.

Fig. 5 (c) shows three-dimensional fence diagram of 12 tomograms in the downtown area of Muan-eup. The surface of the fence diagram is covered by the buildings of more than 4 stories and heavy traffics. Anomaly marked as 'A' corresponds to the cave-in of Fig. 5 (a). 'D' is image of the water-filled cavity and it was confirmed by drilling followed by this survey. Low resistivity anomalies marked as 'B' and 'C', which are developed in the shallow parts of sections, are interpreted to be due to clays which are filling the cavities formed by dissolution of weathered limestone. In many boreholes, clay layers, which are direct indicator of cavity, have been hit just beneath the weathered limestone and our interpretation is based on these results.



(a) (b)

Fig. 6. (a) Distribution of anomalous zones by the interpretation of crosshole dc resistivity tomography images. (b) Estimation of ground stability by the numerical analysis of rock mechanics, assuming the constant load of five-storied building.

5. Discussion and conclusions

In Fig. 6 (a) of spatial distribution of anomalous zone, we can find that the shallow cavity zone filled with clay is widely distributed. In tomograms, most of them are imaged in the similar fashion of the anomalies of 'B' and 'C' of Fig 5 (c). In this area, ground subsidence at rural area as well as urban area had been reported. Since 1990's, however, ground subsidence has occurred more than 10 times, and the occurring rate has been abruptly increased comparing that of past, which implies that the subsidence phenomena in this area is closely related not only with underground limestone cavities but also with the pumping quantity of ground water. After 1970's and 80's, the demand of groundwater has been greatly increased due to the rapid industrialization and civilization, which resulted in the excessive pumping of groundwater eventually. We can easily imagine that a part of clay-filled shallow limestone cavities has been washed away by the excessive pumping of groundwater. Therefore, the occurring rate of ground subsidence should be increased, since only the weak weathered rock or soil would cover the empty space formed by washing out of clay.

Comparing Fig. 6 (a) and Fig. 4, we can recognize that shallow limestone cavities are distributed mainly at the contact zone of limestone and granite, particularly in the vicinity of granite intrusion into limestone. Such a distribution implies that the development of limestone cavities including shallow ones would be closely related with the geological structure, and furthermore, setting and understanding the geological structure would be very important even when targets would be confined in very small area.

Subsurface models have been established for the analysis of ground stability based on the images of dc resistivity tomography, and Fig. 6 (b) is the estimation of ground stability, a result of the numerical modeling of rock engineering analysis. Reinforcement works have been undertaken based on the results of geophysical and rock engineering investigations.

The results discussed so far led us that the integrated geophysical surveys are good approach to explore and to image limestone cavities causing geological hazard. In particular, we could understand that cavity itself is, naturally the main cause of ground subsidence, and the excess pumping of groundwater can trigger or promote the geological hazard. When target area is highly civilized and surface geophysics to delineate the regional geology cannot be applied, it may be a good alternative approach to interpret jointly the results of surface geophysical investigation outside the target area and those of the detailed survey inside it.

References

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