Geomatics Technologies for Hazards Mitigation

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Abstract Three modern geomatics technologies (Global Navigation Satellite Systems GNSS, Geospatial Information System/Science GIS, and Remote Sensing RS) can have significant contributions to hazards mitigation. GNSS is used to precisely monitor the deformations at scale from global, regional to engineering structures in real time mode or in post-processing mode; GIS offers powerful tool to manage high volume of spatial data in both vector and raster forms, a number of spatial analysis functionalities, and ability to display and visualization of the data in various ways; RS with its capability of acquiring both geometric and physical information of objects under study is an outstanding tool for many kinds of studies in a larger area. Although GPS and RS are mainly used for data acquisition and GIS for data management and analysis, they are integrated in many applications. This paper presents the recent developments in these technologies with a focus on hazard mitigation. A particular emphasis will be in the area of earthquake engineering.

1. Introduction

There are three important geomatics technologies, which have significant contributions to hazards mitigation: Global Positioning System (GPS), more precisely GNSS (Global Navigation Satellite System) including GPS, Russian GLONASS and European Galileo, Geographic Information Systems/Science (GIS), and Remote Sensing (RS). GPS can provide precise time transfer, precise positioning and velocity, and atmosphere sensing; GIS offers powerful tool to manage high volume of spatial data in both vector and raster forms, a number of analysis functionalities such as spatial queries, attribute queries, overlaying analysis, two- and three-dimensional spatial analyses, and ability to display and visualization of the data in various ways; RS with its capability of acquiring both geometric and physical information of objects under study is an outstanding tool for many kinds of studies in larger areas, such as land use detection, agriculture crop classification, mapping of vegetation, soil, and forestry, assessment of water quality, environment monitoring, ground subsidence, etc. The images, in particular high resolution satellite images, can be used as a base, which other information can be overlaid on or used in conjunction with. Although GPS and RS are mainly used for data acquisition and GIS for data management and analysis, they are integrated in many applications.

'A hazard is a perceived natural event which threatens both life and property – a disaster is the realization of this hazard.' (Frampton, et al., 2000). Figure 1 shows a disaster management cycle. The geomatics technologies have been used in all the phases of mitigation, preparedness, response, and recovery in the management cycle. During the mitigation phase, GIS is used for managing large volumes of data needed for the hazard and risk assessment, for planning of evacuation routes, for designing the centers for emergency operations; during the preparedness phase GIS, RS, GPS and other relevant sensors are integrated in the design of disaster warning system; during the response phase GPS integrated with other sensors, and GIS are needed for search and rescue operations; during the recovery phase GIS and RS images are used for organizing the damage information and the post disaster census information and in the evaluation of sites for reconstruction.

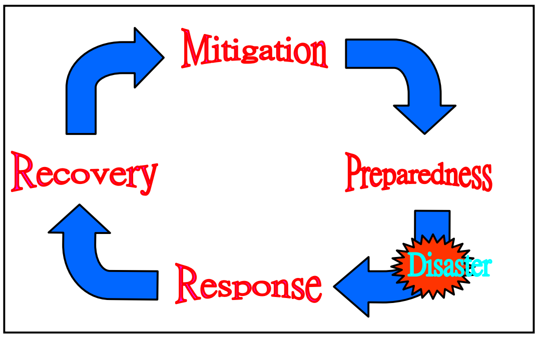

Figure 1 Disaster Management Cycle

This paper first briefly describes the developments in three technologies, followed by example applications. Further studies are finally presented.

2. The developments of GPS, GIS and RS technologies

When used in monitoring, there are two basic GPS positioning modes, i.e., the static and kinematic positioning. The static positioning requires a GPS receiver be stationary over the time of observation. It can only be used to monitor objects that move or deform very slowly. The data accumulated over the observation period are combined to derive the position of the receiver antenna. The measurement accuracy of the static positioning mode depends on the length of a baseline (the distance between a reference station and a monitored station, both equipped with a receiver) and the length of the observation time. The shorter the baseline is, and the longer the observation time is, the higher the observation accuracy will be. Therefore, for a given baseline length, it is always possible to observe long enough to achieve the desired survey accuracy if the monitored object moves/deforms slowly. For the kinematic positioning, the position of a monitored point is calculated for each epoch of observations. The accuracy of the method, especially the accuracy of the real-time kinematic (RTK) method is usually in the range of sub-cm to a few cm.

The advantages of GPS in monitoring deformations include: operation 24 hours a day and in all weather conditions; no need to have inter-visibility between stations; highly automatic once the installation is complete; and able to provide 3D information. The current sampling rate of a receiver is high, e.g., upto 20 Hz, which may be good enough for many monitoring projects. However, GPS surveys require good sky visibility.

The main sources of errors in GPS surveys are multipath effects, cycle slips, troposphere delay and antenna phase centre offsets/variation. The current research efforts concentrate on the mitigation of multipath effects, resolution of integer ambiguities, and psuedolite-augmented GPS positioning.

Department of Land Surveying and Geo-Informatics (LSGI) at the Hong Kong Polytechnic University have done an intensive research in GPS. We developed: a multi-antenna system, which makes GPS monitoring surveys more affordable; psuedolite-augmented GPS precise survey system, which improve positioning accuracy in the areas where no enough satellites can be tracked; methodologies for ambiguity resolution and validation, and mitigation of multipath effects; an accurate and reliable navigation system by integrating GPS, gyro, DR, and map matching; and we studied water vapor and electronic content distributions in the atmosphere with GPS.

GIS posses the analytical capability for decision making and data integration capacity in each disaster phase and can be used for risk assessment, hazard mapping, warning and forecasting for natural disasters like floods, forest fires, landslides, earthquakes and tropical cyclones. Several disaster management systems have been developed with GIS as their platform. GIS can perform the following tasks:

- Effectively and efficiently store, manipulate and integrate various data types related to natural phenomenon with different format.
- Manage data in real time, integrate data on fly allowing emergency managers to visualize and analyze events as they unfold. Besides, the wireless technology allows dynamic data exchange from field back to the geo-database in office.
- Assess natural vulnerability and hazards such as floodplains and areas of earthquake activity; analyze the risk and determine what is most likely to happen in high-risk areas based on historical data; produce the results in detailed maps and analytical reports. Analyzing hazard and risk information with demographics can help determine who will be affected and assessing the needs priority.
- Spatial analysis can be performed to find out the factors and elements related to the hazard. It can model the disaster behavior and estimate the damage loss through multidimensional analysis.
- Produce a buffer zone in the disaster area and estimate the population affected in the surroundings. It is also possible to identify the shortest route between shelter centers and the victims avoiding a dangerous area.

LSGI has a strong group in GIS research. Our research areas cover both theoretical and technological aspects. The theoretical research includes Voronoi diagram for GIS; marine GIS; multi-scale GIS models and generalization; spatial relationships in GIS; uncertainty and spatial data quality in GIS; and 3D and dynamic GIS data model and structure. The technological research includes: R&D program in transport information system (TIS); the integrated GIS and virtual reality for cyber city. Under the R&D TIS program we developed the approach of map matching for navigation, and multi-mode public transport information query and guidance system EasyGo; developing location based services

(LBS) for many applications with mobile technologies.

Remote sensing basically refers to measurement at a distance. More precisely, it is concerned with the detection and measurement of variation in electromagnetic energy (EM). It can be classified into passive and active systems. RS uses satellite images of various spatial resolution and multi-spectrum to extract information of interest. There are four major resolution characteristics determining the type of geospatial data that can be detected by remote sensing systems:

- Spatial resolution determines the ability in recording spatial details and refers to a measure of a smallest object that can be identified by the sensor, or the area on the ground represented by each pixel. Currently sub-meter resolution images are available;
- Spectral resolution refers to the electromagnetic radiation wavelengths to which a system is sensitive. Many RS systems record energy over several separate wavelength ranges at various spectral resolution, referred to multispectral sensors. Advanced hyper-spectral sensors detect hundreds of very narrow bands throughout the visible, NIF, and mid-infrared portions of EM spectrum. Their very high spectral resolution facilitates fine discrimination between different targets;
- Radiometric resolution is the smallest difference in radiant energy that can be detected by a sensor;
- Temporal resolution is the frequency of RS data collection and refers to the length of time it takes for a satellite to complete one entire orbit cycle.

Commonly used active systems include Interferometric Synthetic Aperture Radar (InSAR), a microwave system, and LIDAR (light detection and ranging). Unlike InSAR system, LIDAR is not imaging system. Instead, it measures the distance to the earth surface.

RS techniques has been widely used for land use/cover classification, mapping of topography, vegetation, soil, etc; change detection; and environment study, like air quality, water quality, heat island. An important application area is monitoring of landslide and ground movements with InSAR. LSGI has a RS group working on air quality monitoring, urban heat island, and InSAR.

3. Example applications of geomatics technologies

GPS as monitoring tool

<u>Monitoring of crustal movements</u>

Very dense permanent GPS networks (some are continuously monitoring arrays) have been set up in many parts of the world to study crustal deformations. They can

- provide regional coverage for estimating earthquake potential;
- identify active blind thrust faults and test models of tectonic movements in the region;
- measure local variations in strain rate that might reveal the mechanical properties of earthquake faults;

- measure permanent crustal deformation, in the event of an earthquake, not detectable by seismographs, as well as the response of major faults to the regional change in strain.

Monitoring of engineering structures

Many case studies/tests have been carried out to monitor tall buildings and other types of engineering structures. For instance, we monitored Di Wang Tower in Shenzhen, China during typhoons (Chen et al., 2001). The main issues were to separate the deformations and multipath effects. 12 GPS receivers were installed on Humen Bridge in Guang Dong Province, China that has three suspended spans of 302 m, 888 m and 348 m long (Xu et al., 2001). 10 of the GPS receivers were on the bridge deck and one on each of the two bridge towers. The data sampling rate of the GPS receivers is 5 Hz. Accuracy at centimeter level for single epoch solution is achieved. Wong et al. (2001) reported a comprehensive Wind and Structural Health Monitoring System (WASHMS) for the three major cable-stayed bridges in Hong Kong, the Tsing Ma Bridge, the Kap Shui Mun Bridge and Ting Kau Bridge. 29 dual frequency GPS receivers are used as part of the WASHMS, with 27 installed on the bridge decks, cables and towers of the three bridges and 2 on nearby building roof as reference stations. The data sampling rate is 10 Hz. The receivers on each bridge are first connected to a local data acquisition station that is linked to the GPS general data acquisition center, all through fiber optic cables. The data are processed with a total time delay of 2 minutes from data acquisition to result display. The accuracy of single epoch solution is around 1 cm in horizontal direction and 2 cm in vertical direction.

GPS multi-antenna system for monitoring landslides

The concept of multi-antenna GPS monitoring system has been explored by Chen et al. (2000). The basic idea of the method is to connect multiple GPS antennas to one receiver through specially designed hardware. The cost of a GPS monitoring system is greatly reduced, so that GPS becomes an affordable monitoring tool. Our developed system has been used in many projects, in Taiwan, Korea, and China. Figure 2 shows an example of the multi-antenna system to automatically monitor a landslide near a hydropower station in south-west China.

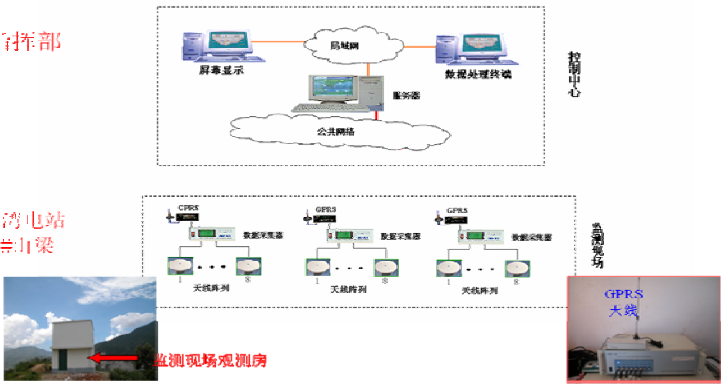

Figure 2 A Multi-antenna GPS Monitoring System

PL-augmented GPS survey system for dam monitoring

The accuracy, availability, and reliability of GPS surveys are much dependent on the number and distribution of GPS satellites being tracked. Many survey environments (like in urban areas, deep open-pit mines, valleys) limit the number of visible satellites and therefore deteriorate the survey accuracy. Moreover, some engineering projects require higher positioning accuracy in a particular direction, e.g., a higher monitoring accuracy required in the direction perpendicular to the dam axis. To overcome the limitation and meet some special requirements, ground-based “satellites”, called psuedolites (PLs), can be added into a GPS survey system to strengthen positioning geometry, which is often referred as the PL-augmented GPS technique (Chen and He, 2008). A pseudolite is a signal generator, broadcasting GPS-like signals. A modified GPS receiver can then receive both GPS and PL signals. A hydropower dam in a valley in China was tested. GPS signals from southeast sector are blocked by mountains (see Figure 3). In the first simulation 3 PLs are placed at elevation angle of 5° and different azimuth of 110°, 180°, and 230° respectively. To study the effect of PL placement, PL1 is also re-allocated to 1’. Figure 4 shows the values of GDOP, with different scenarios. It is clear the placement of PL significantly improve positioning geometry.

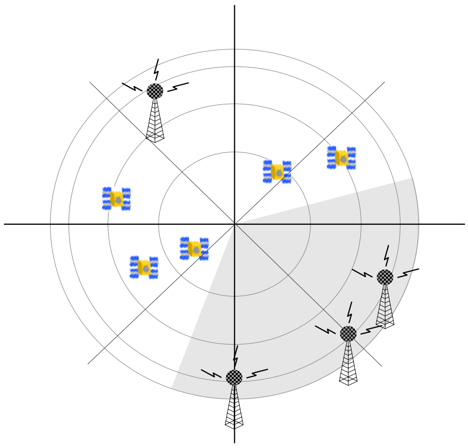

Figure 3 Integration of GPS and PLs for Monitoring of a Dam

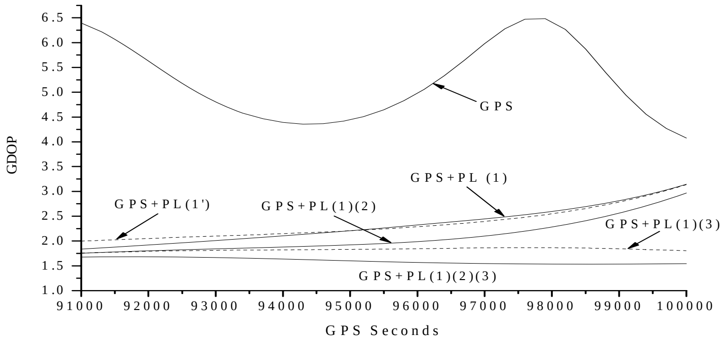

Figure 4 GDOP Values

GIS as base for disaster management systems

Earthquake-related disaster management systems

Different disaster management systems have been developed worldwide using GIS as a platform, such as HAZUS (hazard in the US), RADIUS (risk assessment tools for diagnosis of urban areas against seismic disasters), EPEDAT (early post-earthquake damage assessment tool), Disaster Information Query System (DIQS), Earthquake Database Analysis and Management System (EDAMS) and EEWS (Earthquake Early Warning System in Japan). These systems are used to estimate the levels and costs of damages and impacts on buildings and facilities, to assess vulnerability of earthquake hazard, generate estimated scenarios for potential or probabilistic earthquakes occurred in an area, to document and illustrate crustal structures, seismicity, and deformation of active crusts into a predictive tectonic model, to provide uniform geospatial databases in order to allow the web-accessibility and applications for urban natural hazard and resource issues, to report seismic intensities with names of areas and provide information about the hypocenter and magnitude of an earthquake, or to display analyzed results and information with overlaying on thematic maps.

Automatic and real-time disaster management systems for floods

GIS technology has been adopted to develop different automatic and real-time disaster forecast systems for monitoring floods. The system receives hydrologic data and rainfall information, forecasts river levels and estimate potential flooding area. The system outputs will be used for implementing measures to reduce the flood damage. Some typical examples are the Gezhouba Hydropower Station management information system (GHSMIS), Early Warning System, MIKE 11, NEXRAD, Storm Water Management Model (SWMM), Digital Flood Insurance Rate Maps (DFIRM's), and Flood Mitigation Assistance Program (FMA).

Management and analysis of monitoring data

We developed systems to managing and analyzing monitoring data for landslides and bridges.

InSAR for measuring ground deformation

InSAR technique for monitoring ground subsidence

We used the technique to measure the ground subsidence of Hong Kong airport, and city of XiAn. Figure 5 shows the correlation between InSAR derived ground settlements and leveled results at the airport. The comparison between the results from two techniques indicated the InSAR can provide sub-cm accuracy. City of Xian continuously subsides due to withdraw of underground water. We recently employed InSAR technique to trace its ground subsidence history. Tables 1 and 2 give the comparison between the InSAR results and the other techniques during the periods 92-93, 96-97; and the period 2006-7, respectively. The results are quite consistent, though there is some discrepancy.

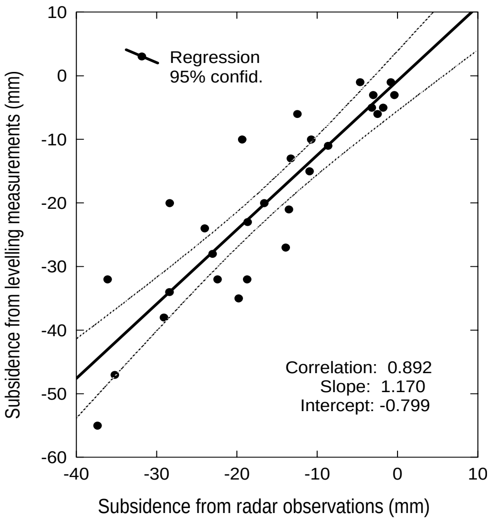

Figure 5 Correlation Between the Results from Leveling and InSAR at Hong Kong Airport

Table 1 Difference of subsidence rate (cm/year)

		92-93			96-07	
point	leveling	InSAR	Diff.	leveling	InSAR	Diff.
1	-2,5	-1.5	-1	-8	-9	1
2	-7.6	-7.2	-0.4	-11	-12	1
3	-13	-7.8	-5.2	-9	-10	1
4	-14.7	-13	-1.4	-15	-15	0
5	-14	-13	-3	-14	-15	1
6	-11	-10.5	-0.5	-15	-13	-2
7	-15	-14	-1	-11	-13	2
8	-6	-6	0	-10	-11	1
9	-12	-13	1	-13	-15	2

Table 2 Comparison between InSAR and GPS results (cm/year)

Area of interest	area 1	area 2	area 3	area 4
GPS	-1.9	-4.1	-2.4	-1.9
InSAR	-0.6	-1.2	-1.8	-1.5

<u>InSAR for measuring displacements of earthquake</u>

We (Liu, et al., 2004) studied the co-seismic deformations of Chi-Chi earthquake on 21/9/1999 with the InSAR technique. Figure 6 shows the displacements, which are in consistence to the terrestrial survey results and the predicted with a tectonic movement model.

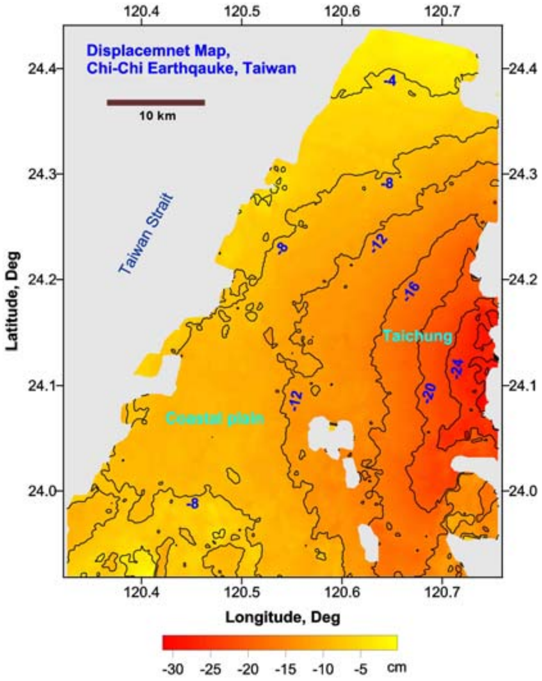

Figure 6 Post-earthquake Displacements

4. Future research

A key limitation of the current GPS technology is its insufficient monitoring accuracy and reliability, especially in less favorable environments, such as poor sky visibility, multipath-sensitive sites. For short GPS baselines as in most of the cases of structural monitoring, the typical positioning accuracy from single epoch GPS observations (dynamic monitoring) is at cm level that is often lower than the requirement. Therefore, it is an important task to further reduce the errors in GPS measurements.

Multipath is one of the main error sources for GPS monitoring. Although there are several approaches/strategies developed, further investigation on the proposed approaches or development of new approach is needed. In addition, there are times when GPS gives results with gross errors (we often see spikes in coordinate time series). It is therefore important to carry out real-time quality assurance to detect and remove problematic observations. Another related problem is poor satellite geometry in some sites. PL-augmented GPS system is a solution. Several issues are needed to be solved before the technique can be placed in practical uses. Further studies should be made on site specific errors such as those typically encountered on a cable-stayed bridge deck where the bridge deck, tower, cables, water surface underneath the bridge may cause both multipath and diffraction errors.

Studies also need carrying out to optimally integrate GPS and other sensors, like accelerometers. The integration will overcome the shortcomings of each and result in the development of accurate and reliable monitoring technologies.

GIS is very useful in each phase of disaster management. However, most of existing systems are only concerned with one type of disaster, in one or two phases of disaster management. Most of them are only in the preparedness phase. They can only perform one or two tasks such as data analyzing and forecasting and warning. Besides, the software is always not user friendly that general public is uneasy to assess. We know that the success of disaster management is greatly dependent on the awareness and participation by general public. Thus, widespread of GIS software and user-friendly and flexibility for customization to encourage public interest is very important for future development of GIS in natural disaster management.

Mobile technology should be further developed for disseminating natural disaster related information. For instance, the position of a mountain fire can be precisely located by using mobile positioning or GPS positioning technologies and the location information can be immediately transferred to the control centre in fire service department and disseminated by the centre. The general public can thus receive this information through mobile devices, such as mobile phone or PDA. The realization of this new service relies on a further development of integration of GPS and mobile GIS. The three-dimensional (3D) GIS for natural disaster environment modeling is another area for further development. Many disaster managements need 3D GIS for 3D real world environment visualization and, and further more spatial analysis. Such application areas may include, for example, affections of earth quake on 3D buildings, fire and simulation in a 3D environments, such as in mountain areas and high building, relationships between landslides and geological environments (in 3D). In order to present these 3D environments, an integrated underground and above surface 3D GIS model need to be developed. These include conceptual and logical 3D GIS models, and implementation algorithms.

Temporal and dynamic GIS should be further developed for the management of dynamic monitoring data on natural disaster. Monitoring natural disaster is a long term and continuous task. For these, larger amount of spatial related time series monitoring data, including dynamic remote sensing and GPS data, need to be managed in an integrated GIS and database management system. Accordingly, an efficient temporal and dynamic GIS is to be further developed.

There are several issues to use InSAR for deformation monitoring, in particular how to improve accuracy. Major issues are geometric distortion, spatial and temporal de-correlation, and atmosphere effects.

Acknowledgement This study was sponsored by Hong Kong Research Grant Council (PolyU5134/06E).

References

Chen, Y.Q., Ding, X.L., Huang, D.F. and Zhu, J.J. (2000) A Multi-Antenna GPS System for Local Area Deformation Monitoring, Earth, Planets and Space. Vol. 52, No. 10, pp. 873-876.

Chen, Y.Q., Huang, D.F., Ding, X.L., Xu, Y.L. and Ko, J.M. (2001) Measurement of Vibrations of Tall Buildings with GPS: a Case Study, Proc. of International Symposium on NDE for Health Monitoring and Diagnostics, 6-8 March 2001, Newport Beach, California, USA. pp.477-483.

Chen YQ and XF He (2008). Contribution of Pseudolite observations to GPS precise surveys. KSCE Journal of Civil Engineering, 12(1): 31-36.

Frampton, C. and H. McNaught (2000). “Natural Hazards (2nd Edition).” p3.

Liu GX, XL Ding, ZL Li, ZW Li, YQ Chen, SB Yu (2004). Pre- and co-seismic ground deformation of the 1999 Chi-Chi Taiwan earthquake, measured with SAR interferometry. Computers and Geosciences 30:333-343.

Wong, K.Y., Man, K.L. and Chan, W.Y. (2001) Monitoring Hong Kong’s bridges: real-time kinematic spans the gap, GPS World, July.

Xu, L., Guo, J.J., Dai, L.J. and Lu, Y.C. (2001) Analysis of data from real-time GPS RTK displacement monitoring system on Humen bridge, Geotechnical Investigation and Surveying, No. 1., pp. 47-62. (in Chinese).