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## **Case-Based Reasoning of Man-Made Geohazards Induced by Rainfall on Transportation Systems**

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Additional information is available at the end of the chapter

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### **Abstract**

Due to global warming and environmental change, disastrous natural events have increased in scale and impact, e.g., Typhoon Morakot, in 2009 and 2011 Tōhoku earthquake and resulting tsunami in Japan. Hazard management is becoming increasingly important, making it a necessity to manage risk and fully understand critical scenarios. For example, the National Infrastructure Protection Plan of the United States emphasizes on lessons learned from past disasters. In this chapter, several selected cases of accidents caused by man-made geohazards in Taiwan are studied.

The International Federation of Red Cross and Red Crescent Societies (IFRC) have identified technological or man-made hazards as events that are caused by humans and occur in or close to human settlements. These can include environmental degradation, pollution, and accidents (such as industrial and transport incidents). Accidents due to man-made hazards usually take place suddenly and give very limited time for response for rescue and recovery of function of facilities. Transportation facilities are a typical case. In this chapter, three hazard case studies are considered: a highway in southern Taiwan, a freeway in northern Taiwan, and an airport runway in the Taoyuan International Airport. The causes and the impacts of the incidents are described. These provide valuable lessons for managing this type of man-made hazard.

**Keywords:** infrastructure development, compound disasters, case-based reasoning, remote sensing, UAS

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# 1. Introduction

## 1.1. Background

Climate change is a serious threat that could undo decades of infrastructure development in developing countries. While climate change is a global phenomenon, human activities are altering the local environment and will continue to do so. The Intergovernmental Panel on Climate Change (IPCC) established by the World Meteorological Organization (WMO) and United Nations Environment Programme (UNEP) has concluded that, over the past century, surface temperatures have increased, and associated impacts on physical and biological systems are increasingly being observed [1]. As climate change is altering rainfall patterns worldwide, scientists predict that wet areas will get wetter, dry areas will become drier, and storm tracks will move toward the poles [2]. Intensive rainfall has resulted in extreme flooding and landslides in many parts of the world. Floods in river basins have become the worst natural disaster, causing casualties, leaving people homeless, and disrupting transportation and economic activities. Floods have buried farmland and destroyed homes, factories, railroads, and bridges. Heavy rainfalls also triggered massive landslides.

The International Federation of Red Cross and Red Crescent Societies (IFRC) gave specific definitions on technological or man-made hazards in recent years. Events that are caused by humans and occur in or close to human settlements include environmental degradation, pollution, and accidents. Typical technological or man-made hazards are complex emergencies, conflicts, famine, displaced populations, industrial incidents, and transport accidents. They are all related to human habitat and modern civilization and can especially impact transport infrastructure such as highways and airports. Owners and operators of land transport systems exposed to rainfall-induced hazards are rarely aware of the risk-related concepts. This lack of knowledge affects the assessment of performance objectives and development of preventive measures for the sustainability of infrastructure systems with regard to flood events.

The majority of devastating disasters have occurred as a result of unusually heavy rains. Past events have highlighted the necessity to adjust the required design performance and specification level for new projects. However, these changes may not be cost-effective and require time to implement. Learning from past events can help facility owners and operators plan ahead regarding not only the exposure, but also the vulnerability and criticality of infrastructures. The design according to a specific return period, e.g., 100 years, may be appropriate for a new single infrastructure element. Assessing the impact of climate change on aging infrastructure can be difficult. Thus, the challenge engineers face today is not to control nature, but rather to adapt to it to lessen the adverse impacts of climate change. The wide range of lessons learned from past incidents can help establish a comprehensive approach addressing infrastructure security issues impacting the availability and quality of transport networks.

Engineers today apply Internet technology and remote sensing to provide unique solutions beyond what conventional methodology would normally provide. An unmanned aerial vehicle (UAV), for example, is an aircraft without a human pilot aboard used to perform

scientific observations and investigatory tasks. The UAV payload and flight stability has increased dramatically in recent years, utilizing spatial positioning components, such as Global Positioning System (GPS) and Inertial Measurement Unit (IMU), which are miniaturized to extend the flight time. UAVs also have the advantages of real-time wireless video transmission, low cost, flexibility, and low-level operations beneath clouds. These advantages can compensate for the shortcomings of conventional aerial or space remote sensing due to cloud cover, thus making UAVs an important aid for traditional aerial photogrammetry in obtaining spatial data. This technology enables engineers to learn and improve techniques from a new perspective.

## **1.2. Importance of this issue**

A record high precipitation in southern Taiwan was set with 2,900 mm (114.17 inches or about 9.5 feet) of rain during Typhoon Morakot. On August 10, 2009, a single day record of 1,403 mm (55.23 inches) was set. According to Chris Burt's, "Extreme Weather" [3], the world record for 3-day rainfall is 127.56" on Reunion Island in 1952. Typhoon Morakot caused what officials claimed was the worst flooding in half a century. The number of known dead in Taiwan is 15, while 32 were severely injured. Those figures do not include landslide victims [4].

On April 25, 2010, a landslide occurred on a segment of the Formosa Freeway (Highway No. 3) near Xizhi. A large amount of dirt buried both directions of the freeway. Four cars were buried under the debris, killing four people. Bad hillside anchoring was blamed as a possible cause, as it had not been raining at the time of the collapse, and any earthquake had not been recorded [6].

In July 2014, underground gas lines exploded in the southern port city of Kaohsiung, killing 28. Heavy rainfall caused tremendous difficulties in the rescue efforts. On October 29, 2015, an EVA Airways Corp. aircraft sustained damage to its left horizontal stabilizer caused by the impact of a large piece of asphalt during takeoff on the southern runway at Taiwan's Taoyuan International Airport.

Although the facilities impacted in these cases are governed by different transportation authorities, scattered in various terrains with varying magnitude, the incidents share a common initiating event. This common factor is rainfall. Rainfall can be measured in the modern era with the global network of precipitation gauges. Surface coverage over oceans and remote areas is relatively sparse, but reducing reliance on interpolation, satellite clouds, and precipitation data have been available since the 1970s. Modern engineers may also take advantage of satellite imaging to develop solutions to mitigate problems.

The developing trends of disaster mitigation and management have focused on risk management through analyzing hypothetical scenarios. The National Infrastructure Protection Plan of the United States emphasizes lessons learned from past disasters. It is believed that the governing authorities and decision makers in disaster management organizations may reduce the impact of hazards and the vulnerability of society by utilizing past experience. Executive actions and preventative measures developed considering history may help reduce the potential loss of life and property.

### 1.3. Purpose of this chapter

The purpose of this chapter is to report three unexpected incidents in detail. All these cases impacted transportation infrastructure. Areas examined and addressed include the cause of the disaster; what the engineering solution brought to the problem; and how engineers in Taiwan can prevent a similar tragedy from happening again.

In addition, the utilization of data acquisition from high-resolution photo images obtained through the use of UAVs after the incident will be considered. This enables engineers to assess the current site conditions, perform safety evaluations, and plan mitigation procedures.

## 2. Case studies

The cases discussed are as follows:

- Collapse of Chung Lin Road in Kaohsiung's Siaogang District - subsidence cracked Chung Lin Road for the second time within a year in the aftermath of Typhoon Dujuan in September 2015.
- Landslide on Freeway No. 3 - the slope failed at the 3.1-km mark from the northern end, just north of the Chitu toll station, and collapsed an overpass on April 25, 2010.
- Taoyuan International Airport pavement cracks - Taiwan's largest airport opened on February 26, 1979. Rain seepage into the pavement caused excessive hydrostatic pressure during plane take-off.

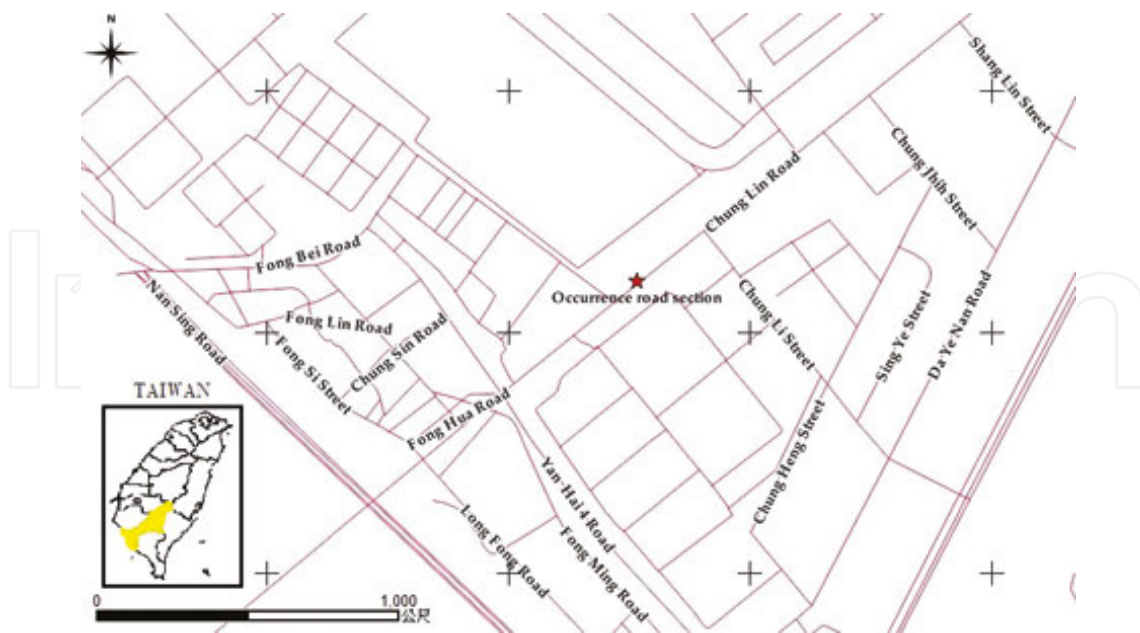
### 2.1. Collapse of Chung Lin Road in Kaohsiung's Siaogang District

The collapse at Chung Lin Road occurred suddenly around 2:00 a.m. on 18th September 2015, in an area where shield tunnelling was being conducted. Due to the collapse, drinking water pipes were destroyed, and electricity was interrupted due to the tilting of power poles. In addition to the inconvenience for residents, nearby petrochemical pipelines were also endangered. This could have jeopardized the supply chains of petrochemical feedstock.

#### 2.1.1. The location of the event

**Figure 1** shows the location of the collapse of Chung Lin Road, Kaohsiung City. The collapse measured 40 m by 10 m. The site is close to the Dalin Refining plant of the Refining Business Division's Operators of The CPC Corporation, Taiwan. The plant includes a number of vulnerable facilities. The distance of the collapse to the nearby oil tanks is only a few 100 m. Fortunately, CPC executed an emergency stop of the transportation of the fluids through the pipelines, and thus no leakage or explosion was triggered.





**Figure 1.** Location of the event.

## 2.1.2. General description of the event

### 2.1.2.1. Introduction

Between 2 a.m. and 6 a.m. on September 18, 2015, an accident occurred in the underground cable shield tunnelling engineering of Taiwan Power Company. It was located underneath the road from Chung Lin Road intersection to the direction of Talinpu in Hsiaokang District, Kaohsiung City and caused the road to collapse. In the early stage of the accident, the road collapse extended to about 40m long and about 10m wide (see **Figure 2**). Power poles tilted and caused an electrical outage. Due to safety considerations, the CPC Corporation suspended the use of 11 hazardous substance pipelines for hydrogen gas, natural gas, pure benzene, toluene, xylene, fuel oil, crude oil, refined oil product, etc. This closure forced the medium-carbon light-oil processing factory to shut down, which led to implementing production and marketing emergency-response measures to avoid affecting Taiwan's oil supply.

Preliminary estimates show that the direct property loss, resulting from this collapse accident, is about 500 million Yuan. This includes the plant facility damage of about 280 million Yuan to CPC Corporation and China Steel Corporation and 220 million Yuan of losses to other affected business and agencies (Kaohsiung Linhai Industrial Park, Sewage Treatment Plant of Linhai Industrial Park, Taiwan Water Corporation, Chunghwa Telecom Corporation, Water Resources Bureau, Kaohsiung City Government, etc.). It is not possible to accurately estimate the indirect losses such as production suspension at CPC Corporation (where the loss in daily capacity was close to 40 million Yuan) and the disruption of raw materials to downstream facilities.



**Figure 2.** Destruction of roadway.

#### *2.1.2.2. Preliminary analysis of causes*

The accident occurred during the underground cable tunneling project of Taiwan Power Company. Due to the failure of the shield tunneling engineering machinery occurring 30 m underground, groundwater flooded into the excavation and caused the road pavement to collapse. In addition to the underground drinking water pipe failures, trees, and utility poles around the road tilted as well. Although the accident occurred at about 2 a.m. on the 18<sup>th</sup> of September, the construction personnel did not formally close the road and notify the impacted pipeline and business units until past 6 a.m. In addition, since the underground pipelines were already damaged, secondary damage occurred during the emergency repair, including oil and water leakage with the resulting environmental pollution. The collapse area continued to expand after the initial accident.

#### *2.1.3. Social impacts*

This incident highlights the importance of underground pipeline safety management. The pipeline was buried before the urban area developed. The side-by-side development of the metropolitan and industrial areas was inevitable due to the limitations of land use. Therefore, the risks to public safety from accidents such as pipeline leakage, explosion from the hazardous substance, and public pipelines buried underneath roads are increased, once these facilities are damaged by the excavation accident.

It is fortunate that this incident occurred early in the morning during the off-peak traffic period. Although there were no casualties, it caused the road collapse and closure, direct losses to the

state business, impacts onto the petrochemical industry operation, and subsequent inconvenience to peoples' lives. The impacts caused by this incident are as follows.

#### *2.1.3.1. Interruption of road passage*

In the accident area, the large-scale collapse destroyed Chung Lin Road, causing its closure, creating inconvenience for local motorists. Fortunately, an emergency road, allowing temporary motor-vehicle access, was completed about 2 months (November 15, 2015) after the accident.

#### *2.1.3.2. Interruption of lifeline infrastructure*

Due to the severity of the collapse, the infrastructure components around the road were all seriously damaged. Utility infrastructures, like power-supply equipment, and communication and public pipelines are also damaged, disrupting the water, power, and gas supplies, interrupting telecommunications and severely affecting the residents' normal life.

#### *2.1.3.3. Impact of industry*

Because the CPC Corporation closed the underground petrochemical pipelines underneath the accident area, the affected petrochemical industry facilities were forced to face the crisis of a production shutdown. Petrochemical raw materials would have to be transported with tank vehicles or alternative pipelines, thus increasing the risk of hazardous-substance transportation incidents on the road.

#### *2.1.4. Lessons learned from the event*

The aforementioned accident can provide the following lessons.

1. Identifying the risks of the construction method selected beforehand would have identified potential accident consequences.
2. Immediate communication with local authorities and industries could have reduced the danger to the public and oil-related pollution.
3. Development of a coordinated contingency plan, in advance, with emergency responders could have reduced the impact and loss caused by the disaster.

## **2.2. Landslide on Freeway No. 3**

Section-3.1K landslide accident of Freeway No. 3 occurred at Mt. Shihgongge at Location 3.25K at 14:29 p.m. on April 25, 2010. According to statistics, this is the most serious landslide accident in the past 36 years on Taiwan's national freeway. The worst landslide on the system occurred near Badu Interchange on the Sun Yat-sen Freeway on September 28, 1974, which caused 36 deaths [5–8].



### 2.2.1. The location of the event

The landslide accident occurred in Madong Village, Qidu District, Keelung City. During the slide, the Dabu Bridge crossing Freeway No. 3 also collapsed onto the freeway mainline, thus blocking traffic (**Figure 3**).



**Figure 3.** Photograph of the landslide at Freeway No.3 (Source: [http://www.nasc.gov.tw/files/duty\\_news\\_files/\\_4251883.JPG](http://www.nasc.gov.tw/files/duty_news_files/_4251883.JPG)).

The accident took place at a dip-slope, with the site elevation varying between 122 m to 182 m above sea level. The dip angle of the strata at this location ranges from 12 to 15°. The geological formations consisted of Daliao Shale and sandstone as well as shale alternations. The lithology of the sliding surface is on a shale formation.

### 2.2.2. General description of the event

#### 2.2.2.1. Introduction

In this large-scale landslide accident, four deaths occurred. The day the event occurred was sunny and free of typhoon, rainstorm, earthquake, and other factors that typically cause landslides. According to subsequent analysis, the possible cause was that, due to side-slope excavation of freeway engineering, the free end of the dip slope toe was exposed (or daylighted). The rock material is block sandstone with shale inter-bedding. A weak surface is likely to be caused between beds. Underground water infiltrates in the sandstone (which has high permeability), resulting in hydrolyzing and weathering on the top of the thick shale, and finally causing sliding failure of weak surface. According to the comparison of topographic data before the landslide disaster (obtained through Airborne LiDAR in April 2006) and the

measured data after the landside disaster, the collapsed earth and stone volume is 165,000 m<sup>3</sup>, the collapse area is about 1.14 hectares, the influenced scope is 2.4 hectares, and the collapse depth is 15 to 20 m.

#### *2.2.2.2. Preliminary analysis of causes*

The site is a mostly oblique ridge with a steep slope in the northwest and gentle slope in the southeast in this region, and it is dip slope in terrain, that is, the stratum tendency and slope direction are close, and in the southeast direction. There are many similar dip slopes along the alignment of the freeway in northern Taiwan. According to the field investigation results, the landslide causes are preliminarily summarized as follows.

1. The disaster was caused by dip-slope sliding.
2. The dip slope at the location is formed through mutual stacking of sandstone and shale, and a slide is likely to occur at the interface of rock layers.
3. The sandstone in the upper layer is seriously weathered, rich in vertical joints, and permeable. The shale in the lower layer has poor water permeability; therefore, a higher water content and water pressure was caused in the interface between the two rock layers, reducing the friction between the rock layers and resulting in a slide.
4. The sliding rock is huge, and it is likely to exceed the original rock anchor capacity, causing the breakage of the sliding rock's connection to the base material.

#### *2.2.3. Social impacts*

##### *2.2.3.1. Interruption of road passage*

The landslide covered six lanes with earth and stone. Three cars were buried, causing four deaths. The Dabu Bridge broke into two sections and fell onto the freeway mainline. Therefore, National Freeway Bureau and National Highway Police Bureau emergently blocked the section from the site north to Sijhih System Interchange of Freeway No.3, and from the site south to Keejin Interchange, leaving traffic flow completely disconnected.

##### *2.2.3.2. Interruption of lifelines*

The traffic shutdown lasted for more than 70 days until the accident section was reopened (June 19, 2010). Commuters in Keelung and other regions had to select alternative routes due to the closure of the collapsed section, adding 1.5 hours for the journey from Taipei to Keelung. Some traffic detoured to the Sun Yat-sen Freeway or provincial highways, causing traffic jams in many locations. People's normal lives were seriously impacted by the closure.

##### *2.2.3.3. Impacts on industry*

The north-south two-way section from Keelung to Taipei of the Sun Yat-sen Freeway suffered traffic jams in rush hours. This added significant transportation time and cost to the import and export traffic from Keelung port.

#### 2.2.4. *Lessons learned from the event*

After the landslide accident, the Department of Transportation organized an academic unit to carry out “investigation work of 3.1K landslide accident of Freeway No.3” to identify the accident causes and study subsequent emergency treatment strategies. The major findings of the investigation are as follows [6–8].

There is a difference in the included angle between the original design section used in the side-slope stability analysis and the actual sliding section. According to the side-slope stability analysis code at the time, the safety factor upon earthquake should be bigger than or equal to 1.1. The calculated safety factor of the original design section is in compliance with the requirements given in the code. However, the calculated safety factor of the actual sliding section is only 0.96 and is not in compliance with the requirements given in the code. Moreover, the side-slope stability safety factor of the actual sliding section under earthquake state is not in compliance with the requirements given in the code. These discrepancies between the original design and actual field-condition calculation results reflect the critical importance of field-surveying accuracy.

Ground anchors were used to restrain the section from sliding, but the anchor forces may have impacted the rock stress distribution and caused tension in the upper part of the slope. This is an area requiring further research and possible adjustment of the safety factors in the existing code.

Of the 572 ground anchors completed in the beginning of 1998, only 58 remained on the side slope after the landslide, with the damage ratio reaching as high as 90%. This reflects the importance of ground anchor and tie-back tensile force in side-slope maintenance.

In earlier inspections, the ground anchor-related investigation was not conducted. In addition, the regular inspection reports were not filled out in detail. Therefore, it is not known whether the pre-stress of the ground anchors gradually relaxed or the tendons of ground anchors were rusted in the period from the time the ground anchors were completed (at the beginning of 1998) to the time landslide occurred. This indicates the importance of regular comprehensive inspection.

The governing authority ignored the collapse risk as well as neglecting the importance of the existing monitoring equipment, so that the use of the landslide detector was stopped without prudent consideration of the potential consequences, indicating the importance of automatic, continuous monitoring.

In terms of treatment and maintenance of soil and water conservation, the slope stability and water-drainage systems should be “considered as a whole.” In future, therefore, for the indivisible places of upper and lower side slopes of highways, the highway administration authority will be specified to be responsible for maintenance of the highway-facility safety. The highway authority will appoint personnel to enter into the public and private land to inspect and test conditions; and the land owner, user, or manager shall not evade, hinder, or refuse this inspection [8].

In future, further research has to be undertaken on whether tension cracks occur in the upper part of the dip slope outside the highway right-of-way impacting the ground anchors, similar to those on the collapsed side slope in this case. This could cause surface water leaking to rock stratum, thus weakening the strength between rock strata, resulting in similar effects as the collapse at this site [8].

### **2.3. Taoyuan International Airport Pavement Debris**

On Thursday, October 29, 2015, an aircraft owned by Taiwan's second largest carrier, EVA Airways Corporation, sustained damage to its left horizontal stabilizer during take-off on the southern runway at the Taoyuan International Airport. This was caused by the impact of a large piece of asphalt from the runway with the stabilizer.

Asphalt blowup in an airport runway is very dangerous for aircraft operations and requires immediate attention. Airport pavement distresses begin with minor moisture leakage, which, when deemed detrimental to aircraft operations, can lead to runway closure. The impact of the runway closure not only delivered a negative message to other countries but also caused a huge loss to the tourism industry.

#### *2.3.1. The location of the event*

The Taoyuan International Airport serves the capital city of Taipei, Taiwan, and the northern parts of the island. Located about 40 km west of Taipei, the facility is Taiwan's largest airport with regular international flights. It is by far the busiest international air entry point in Taiwan and the main international hub for China Airlines and EVA Air. The airport opened for commercial operations in 1979 and is an important regional trans-shipment center, passenger hub, and gateway for destinations in Asia. The airport was formerly known as Chiang Kai-shek International Airport (CKS International Airport), in remembrance of the former president, until the name was changed on 6 September 2006. The number of aircrafts landing and departing from the airport has grown from 150,000 to 200,000 per year. The Taoyuan International Airport handled a total of 35,804,465 passengers and 2,088,726,700 kg of freight in 2014. It is the 11th busiest airport worldwide in terms of international passenger numbers and fifth busiest in terms of international freight traffic.

#### *2.3.2. General description of the damage*

The damage incurred to the EVA Air jet was alleged to cost EVA Airways Corporation close to \$10 million Yuan (US\$ 300,000). The runway maintenance problem at the airport has not only caused flight delays, but the hazard potential has also threatened aviation safety. The original airfield pavements were designed and constructed to provide an adequate support for the various loads imposed by both aircraft and environmental (climate) conditions such as temperature or moisture variations. The runways were also constructed with joints to allow expansion and contraction from temperature changes. The initial investigation of the incident attributes it to hydraulic fluid leaking from aircraft causing erosion of the pavement. A further analysis suggested that the design of the runways was flawed, if that was the main cause of



the damage. However, the Civil Aeronautics Administration and airlines denied that theory of erosion being caused by hydraulic fluids, saying that the detection of such a hydraulic-fluid leak would result in an aircraft being grounded for immediate repairs.

### 2.3.3. *Social impacts*

For airport pavement, distress can be caused by the disintegration of pavement due to axial compression forces generated by slab expansion due to pavement temperature and moisture changes. Blowup usually occurs at transverse joints or cracks in hot weather if they are not wide enough for pavement expansion. If pressure from pavement expansion cannot be relieved, it results in a localized upward movement of slab edges or shattering in the vicinity of the joint [9]. As reported in the Central Region Airport Certification Bulletin, an airport runway pavement blowup case occurred at the Ankeny Regional Airport in Iowa, United States, in the summer of 2011. A similar case occurred in Nepal where a number of international flights in the Tribhuvan International Airport in Kathmandu Nepal were delayed, diverted, and cancelled due to airport flexible-pavement distress during August 2013. Pavement-related failure incidence around the globe shows that pavement deterioration, pavement debris, and mud blowup as major airport safety concerns are common phenomena in airports.

Pavement distress and the resulting Foreign Object Debris (FOD) (a term referring to a foreign substance or debris that can cause aircraft damage) on airport runways are dangerous for aircraft operations. If FOD occurs on airport runways without prompt discovery and removal, an aircraft can be damaged during takeoff or landing. A serious accident can result, and consequently the passengers aboard the aircraft may be injured or may lose their lives. The runway needs to be closed for repairing distress and removal of FOD. A closed runway causes economic losses resulting from flight delays, cancellations, etc. To avoid the recurrence of similar incidents, the Taoyuan International Airport Corporation (TIAC) has changed the pavement at both ends of the runway from asphalt to cement, adding that the firm plans to procure an FOD detection system—the same as the one used at the Hong Kong International Airport—to monitor runway conditions at Taoyuan Airport.

### 2.3.4. *Lessons learned from the event*

Pavement health monitoring employing advanced technology to allow the assessment of the structural reliability and detection of structural changes is an effective solution to prevent aircraft accident and damage caused by poor pavement performance and FOD. However, the full solution of the airfield pavement debris problem should start by analyzing its fundamental causes. An investigation of the compacted backfill under the airport runway slab using ground-penetrating radar (GPR) showed substantial voids. In addition, after a continuous rainfall, a great deal of moisture seepage occurred through the construction joints. Under a cyclic surface loading (resulting from airplane takeoff and landing), the hydrostatic pressure generated by the noncompressible fluid washed away the foundation substrate (from small to mid-size soil particles) leaving more spaces for additional water. The negative cycle continues until—when there are not enough voids to accommodate or relieve the pressure—the slab cracks occur.



To resolve the particular issue, Taiwan engineers have gone through a series of laboratory tests to imitate the phenomena in a controlled environment. A pilot program implementing Hydrostatic Pressure Relief Technology has been proposed and is under construction. The idea came from the pressure-relief mechanism used under railways in Europe where a permeable geosynthetic layer is installed underneath the slab. The Hydrostatic Pressure Relief Technology has also been adopted successfully by developers and building contractors in more than 60 cases where buildings are subjected to underground water buoyancy. In addition, through a continuous remote monitoring and review of settlement, seepage, and pore-water pressure, the proposed system is expected to provide a rapid, simple, and cost-effective solution to the airfield pavement-deterioration problem.

### **3. Topographic change analysis of man-made geohazards with unmanned aerial vehicles**

An unmanned aerial vehicle (UAV) (also known as a drone) is an aircraft without a human pilot aboard used to perform scientific observations and investigation tasks. Since UAV payload and flight stability have recently increased dramatically, spatial positioning components, such as GPS and IMU, have been miniaturized to extend the flight time. UAVs also have the advantages of real-time wireless video transmission, low cost, flexibility, and low-level operations under the cloud base [10]. These properties can compensate for conventional aerial or space remote sensing subject to the shortcomings of cloud cover; hence, it becomes one of the important aids for traditional aerial photogrammetry to obtain spatial data. Many kinds of sensors, e.g., hyper-spectrometer, thermal imager, or LiDAR sensors, can be mounted on a UAV, although the most commonly used sensor is the consumer-grade digital camera [11].

The UAV has been widely used in the world, including maritime search and rescue, forest conservation, soil and water conservation, natural disaster investigation, and so on [12–19].

The authors used an eBee UAV for collecting high-resolution geospatial data for golf-course maintenance [20]. The study showed that the UAV was efficient and of low cost for producing orthophoto of 3-cm resolution and 3-D terrain point clouds for a golf course. The benefits derived from geoinformatics in the maintenance and management of a golf course had also been demonstrated. Since there was no spatial data as a map database for the golf course, the results indicated that the very high-resolution 3-D spatial information can provide an important database to assist the facility staff in performing improvement planning and design, utilizing spatial analysis tools. Moreover, golf players can access the spatial information services using spatial query functions to learn where various features and amenities are located. This could provide course managers an excellent marketing tool for providing golf players with better value-added services.

Another UAV study was conducted for a case of drainage planning. For mapping the efficiency and higher visual communication for drainage planning, a combination of aerial survey with unmanned aerial vehicles and a supplementary field survey was conducted to produce very high-resolution orthogonal-rectified images and 3-D terrain data in the sludge sedimentation

tank area of the Shihmen Reservoir, northern Taiwan. The result of accuracy evaluation with 25 check points shows that the mean errors in X, Y, and Z are 7.57 cm, 8.36 cm, and 23.4 cm, respectively. According to the topographic mapping standard in the scale of 1/1000, the mean error is acceptable for aerial mapping [21]. The abovementioned cases showed that UAVs can be effectively applied to collect information for the assessment of structure deformations and damage when man-made geohazards take place. The results can be used for strengthening the structures or developing other measures for mitigating hazards.

### 3.1. Procedures of data acquisition with a UAV

First, a flight plan can be made based on the requirements of the emergency mission and the sensor system used, including items such as the specifications of the camera used, overlap ratio of photos, and the condition of the disturbed ground surface. UAVs come in many shapes and sizes. The characteristics or specifications of the UAV ultimately lead to the operator's decision as to which platform will best fit the survey application. These key attributes and acting on them will ensure that the mapping mission is a success. Two main types of UAV are available that are suitable for surveying work. The first type is a fixed-wing model. In general, the stability of a fixed-wing UAV is good for precision mapping for topography, but it does have certain restrictions in taking-off field and operation conditions. The second type of UAV is a rotary-blade, or propeller-based model. Unlike the fixed-wing models, these mini-copters are able to fly in every direction, horizontally and vertically, as well as hover in a fixed position. This makes them the perfect instrument for detailed inspection work or surveying hard-to-reach areas such as pipelines, bridges, power lines, and rail tracks. A fixed-wing UAV can be suitable for a wide area survey, whereas a rotary UAV can be better adopted for complicated terrain and restricted open space [22].

Secondly, control points and check points should be properly selected to cover the survey areas. The quantity of the required points depends on the quality of the final outputs required. If they are digital terrain models and orthophotos of high quality, this will require high quality of the control points. Otherwise, a few points (such as 3 points) can be enough for a reconnaissance. Subsequently, the geodetic coordinates of the control points can be measured by Real-Time Kinematic (RTK) satellite navigation or measured with a Control Entity Database using control entities of aerial images. In addition, weather conditions are critical for image quality due to the illumination and vibration due to wind speed. Before an aerial sortie, all functions of the platform and sensor should be carefully checked.

After imaging, all captured images are imported into a postprocessing software such as Pix4D, AgisoftPhotoScan, or Postflight Terra 3D software to perform photogrammetric processing of digital images and to generate 3-D spatial data. For example, it is possible to apply Agisoft-PhotoScan for a full automation of the postprocessing, including image registration for orientations and digital elevation modelling, with either traditional aerial photographs or digital images [23]. An SfM (Structure from Motion) algorithm is adopted in the software to accommodate the situation when there are no control points and/or inner parameters of the camera. SfM will retrieve the spatial coordinates of objects in the stereo-pairs by reconstructing

the location and orientations of all the images captured in the air. The procedures of SfM approach include:

1. Reconstruction of the locations and orientations of each stereo-pair;
2. Construction of the trajectories of the camera; and
3. Construction of the 3-D landscape.

Generally, the payload capability of UAVs is very limited. Consumer digital cameras are used to replace the conventional metric camera. Thus, it is a prerequisite to calibrate the digital camera to obtain its parameters, including the inner orientation parameters and distortions. These parameters are entered into the postprocessing software. Feature points and conjugate points can be retrieved in the software with a function such as AlignPhotos. Subsequently, photo centers and orientations of each exposure can be derived. The second stage of the procedure is to use the function of Build Sense Cloud to generate point clouds on the basis of a bundle adjustment and ray-tracing approach. This is optimized with filtering out outliers. The third stage of the procedure utilizes the function of Build Mesh to construct a TIN (Triangular Irregular Network) for the point clouds generated in the previous stage. The digital surface models (DSMs) can be generated. The fourth stage of the procedure is applying the function of Build Texture to construct the texture of the 3D models by draping corresponding textures expressed on aerial photographs. It is noteworthy that this involves the reconstruction of the camera parameters of location and orientations. These parameters are better entered as extra parameters for compensating the automatic reconstruction of the adjustment of aerial triangulations and inner orientations [24]. Accurate stereo-models can thus be established with the exterior orientation of each camera exposure stations. Digital Terrain Models (DTMs) and ortho-photographs can be automatically generated subsequently. Finally, animated videos of the geohazards, the 3D models, and other useful thematic maps such as slope gradient, slope aspect, and contour lines can be derived as well for other geospatial analyses such as earth-volume analysis with Difference of DTMs (DoD) and for assisting in damage assessment and planning mitigation measures.

### 3.2. Suao Landslide Case at the Coastal Su-Hua Section of Highway Route 9

Due to the combined effects of Northeast seasonal winds and Typhoon Nalgae, heavy rainfall induced in the I-Lan area resulted in serious landslides. The Suao Landslide at the coastal Su-Hua Section of Highway Route 9 was located at the 11.8K-km mark. At this site, the entrainment effect of debris flow and toe erosion on the downslope induced a regressive sliding failure at the adjacent road causing the downslope collapse and roadside barrier failure. The rockfall barriers at the upper stream of the nearby Daken bridge were destroyed as well. The incident took place at 05:00 on 9th October 2011. The heavy rainfall lasted 12 h, with an average rainfall at the nearby rain station of 30.5 mm/h with a total rainfall of 418.9 mm. The affected landslide area along the road was 150 m<sup>2</sup>. **Figures 4** and **5** show the photographs captured by the UAV camera. **Figure 4** shows the orthorectified image of the landslide. **Figure 5** shows some selected views of the landslide.



**Figure 4.** The ortho-rectified UAV image of the Suao Landslides (Source: GangYu Corporation).



**Figure 5.** Some selected views of UAV images of the Suao Landslides (Source: GangYu Corporation).

### 3.3. A Dip-slope Landslide on Freeway No. 3

A dip-slope landslide on Freeway No. 3, close to Chidu District of Keelung City, northern Taiwan took place on 25<sup>th</sup> April 2010. The landslide has an area of 11,475 m<sup>2</sup>. UAV was applied as an experiment of emergency response to acquire aerial images of the affected area, to produce stereo-models, and to evaluate the damage for the analyses and interpretation of the disaster [25].

The procedures of UAV operation were as follows. Image acquisition was conducted on 26<sup>th</sup> April 2010, the day after the event. There was a clear sky with light haze. Flight height was 500



m above ground in average. Flight speed was 50 km/h. Ground resolution of the images was about 17 cm. The forward overlap between images is more than 80%. **Figure 6** is a UAV side view of the landslide captured by a rotary-wing UAV owned by the Flying Tiger Helicopter and Skyline Dynamics Co., Ltd. **Figure 7** is a historical photograph of the site taken by the Agricultural and Forestry Aerial Survey Institute (AFASI).



**Figure 6.** UAV side-view of the landslide taken by a rotary wing UAV owned by Flying Tiger Helicopter and Skyline Dynamics Co., Ltd.

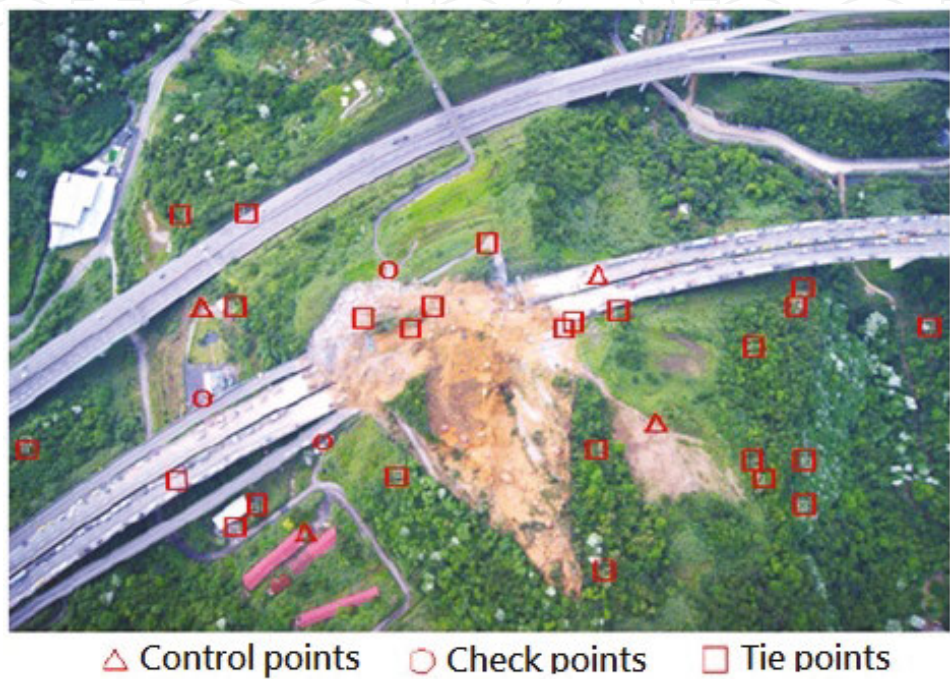


**Figure 7.** Historical photograph of the site taken by the Agricultural and Forestry Aerial Survey Institute (AFASI).

To facilitate the production of stereo-pairs, the stereo-models developed for producing official electrical maps (a scale of 1 to 2500) in 2009 were used for measuring control points of ground features such as building corners and road signs. In total, one vertical control point and three full control points were captured along with three check points for subsequent accuracy assessment. In a later stage, image automatic matching and aerial triangulation were conducted with Erdas LPS and 25 tie points. **Figure 8** shows the locations of all the control points, check points, and tie points.



After the establishment of stereo-pairs, digital elevation models and orthophotomosaics were created. **Figure 9** shows the side boundary of the landslide and the limit of the freeway where the landslide overtopped it. The landslide area is estimated as 11,475 m<sup>2</sup> and the volume 137,571 m<sup>3</sup>, with an estimated material weight of 300,000 tons. These estimates were useful for managing the trucks used for debris disposal.

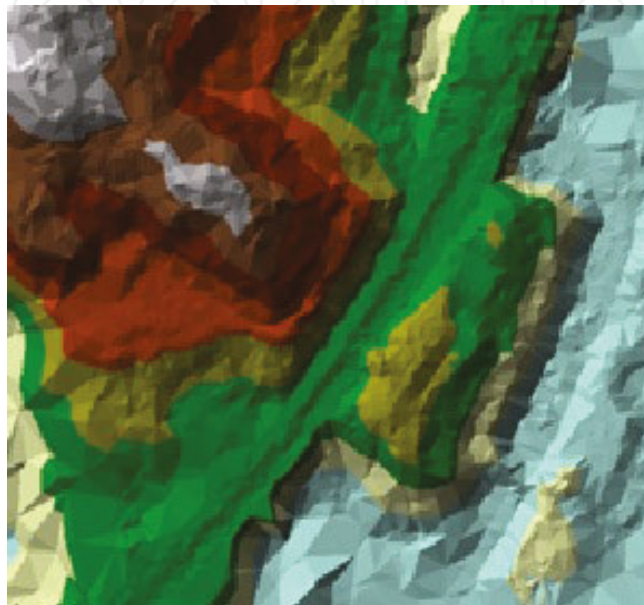


**Figure 8.** Locations of all control points, check points, and tie points [25].

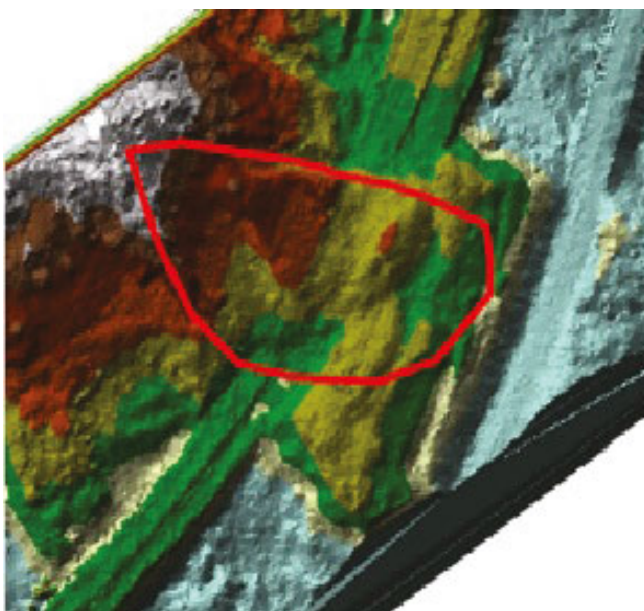


**Figure 9.** Side boundaries of the landslide and the freeway limits [23].

Additional benefits that the decision makers can gain from the results of UAV operations include 3-D schematic models of the landslide (**Figure 10** and **Figure 11**), animated videos, topographic analysis of the landslide, and a comparison of the cross sections prior to and following the event (**Figure 12** and **Figure 13**). To facilitate the process of emergency response, a standard procedure, including UAV operations, can be beneficial and worthy of establishment.



**Figure 10.** 3-D Models prior to the event [23].



**Figure 11.** 3-D models following the event [23].



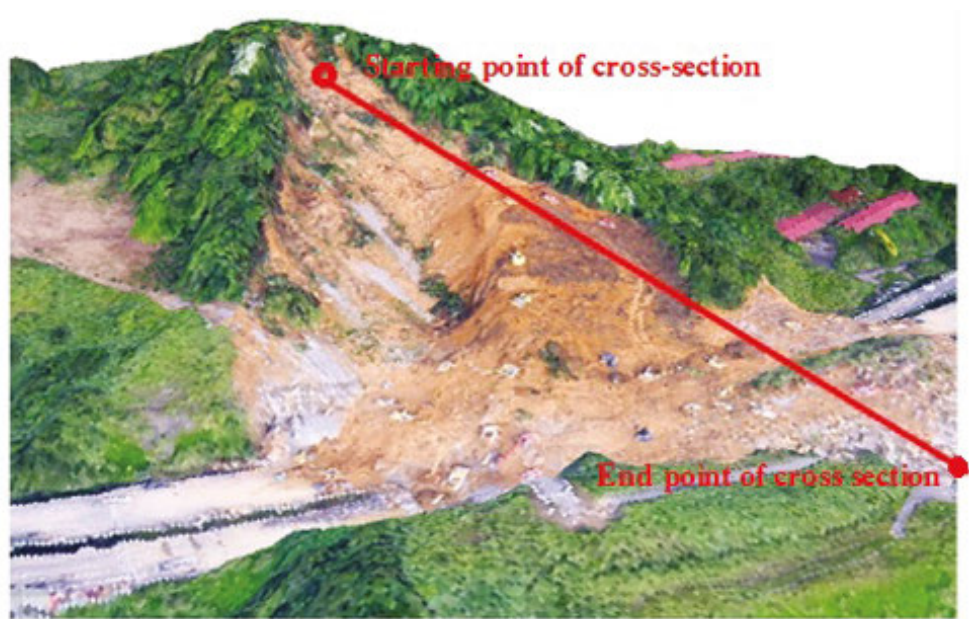


Figure 12. Location of the cross section.

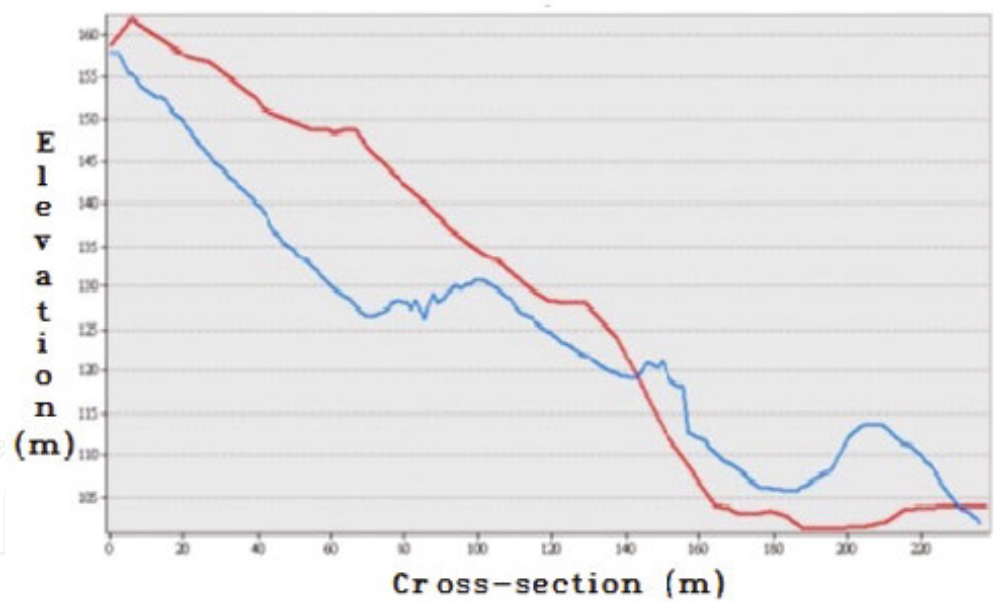


Figure 13. Cross sections for both prior to and following the event.

4. Conclusions and suggestions

The results of the man-made geohazards in the three case studies considered can be summarized as follows:

1. To minimize the impacts and losses due to disasters, information sharing for emergency responses is critical. In addition, preparedness and monitoring of operations are required before any emergency cases occur.
2. The case of Freeway No. 3 showed that the slope stability did not meet the code requirements for earthquake resistance. This was due to the uncertainty of the in situ measurements. Therefore, the accuracy standards, the design parameters for ground anchors, the procedures of regular inspection, and automated sensing for certain vulnerable zones are all important to prevent similar future events.
3. The Hydrostatic Pressure Relief Technology has been adopted successfully by developers and building contractors in more than 60 cases where buildings are subjected to underground water buoyancy. In addition, through a continuous remote monitoring and review of settlement, seepage, and pore-water pressure, the proposed system is expected to provide a rapid, simple, and cost-effective solution to airfield pavement-deterioration problems.
4. UAVs equipped with suitable sensors will become a critical means for assuring the process of design, construction, operation, and emergency response for incidents caused by man-made geohazards. UAVs can be used for quick generation of the DTM, orthophotos, 3-D models, animated birds' eye view, and change detection for assessing hazards. The procedures of UAV applications and productions of 3-D information are presented in this chapter.

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