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Potential for future eruptive activity in Taiwan and vulnerability to volcanic hazards

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Abstract Taiwan is subjected to several natural hazards such as extreme weather, seismic activity or tsunamis excited by earthquakes occurring along the Pacific Ocean subduction zones. Fortunately, Taiwan has not experienced any volcanic activity in historical times, a fact which reinforced the belief that its volcanic centers are by now extinct. During the past decade, volcanological, seismological and geochemical observations have shown that such a belief is erroneous and that two of Taiwan's volcanic centers (Tatun Volcano Group and Kueishantao island) have potential for future eruptive activity. Additionally, there is historical evidence for four submarine eruptions offshore the northern and eastern coast of Taiwan over the last 150 years. The types of volcanic hazards that may affect Taiwan's infrastructure and population are ashfall, pyroclastic flows, lava flows, landslides/volcanic debris avalanches, lahars, phreatic explosions and tsunami. Two of Taiwan's nuclear power plants (and a third whose construction has been temporarily suspended) are close to the volcanic centers and could be affected by ashfall and lava flows, an issue that needs to be addressed by the operator of the plants. Even though the probability of future volcanic activity is low, it has to be recognized that the vulnerability to volcanic hazards for an advanced technological society such as Taiwan's has increased considerably. Volcanic risk therefore cannot be considered insignificant, and its mitigation has to be addressed by a co-ordinated research/monitoring program. Furthermore, the development of contingency plans is a must for such high risk phenomena even if they are considered "low probability" events.

Keywords Volcanic hazards · Tatun · Kueishantao · Taiwan · Eruption · Nuclear power plants

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1 Introduction

As part of the “Ring of fire” that encircles the rim of the Pacific Ocean, the island of Taiwan is significantly exposed to hazards related to solid Earth processes. This is a direct consequence of the location of Taiwan at an active plate boundary where the Eurasian Plate and the Philippine Sea Plate have been colliding since late Miocene (Yu et al. 1997; Chang et al. 2003; Hsu et al. 2009; Fig. 1). The collision of the two plates results in the generation of Taiwan’s orogeny, which first affected northern Taiwan and later migrated southwards (Teng 1996). Seismological and geodetic observations show that northern Taiwan is presently subjected to postcollision crustal extension in a N–S orientation (Kao and Jian 2001; Rau et al. 2008). The Philippine Sea Plate also subducts beneath the Eurasian Plate to the east of Taiwan, forming the Ryukyu subduction zone and the Okinawa Trough which is an actively rifting backarc basin. The westernmost tip of the Okinawa Trough reaches the northeastern part of Taiwan, where both tectonic and magmatic processes are present in the form of normal faulting and of volcanic vents on the seafloor (Kimura et al. 1988; Yamano et al. 1989; Sibuet et al. 1998).

This complex tectonic setting is responsible for high levels of seismicity; therefore, the seismic hazard stemming from potentially active faults in Taiwan is relatively well studied (see for example Shyu et al. 2005). Over the last three decades, the rapid economic growth of Taiwan has resulted in the development of expensive infrastructure (high-speed railway, metro system in major cities) and industrial units (microchip factories, nuclear power plants), as well as the concentration of millions of people in civic centers in the north of the island such as Taipei or Taichung. All these factors have increased the vulnerability of Taiwan and contributed toward the funding of several investigations related to seismic risk mitigation especially after the 1999 chi–chi earthquake. Even though volcanic activity can also be a significant source of hazard for people and facilities, Taiwan has been lucky enough not to have witnessed a volcanic eruption in historical times. Unfortunately, this has reinforced the false belief that Taiwan’s volcanic centers are by now extinct and very little attention has been paid either to the hazards stemming from future volcanic activity, or to mitigation of the risk.

This paper examines the eruptive potential of Taiwan’s volcanic centers based on all available information as well as the vulnerability of its people and infrastructure to volcanic hazards. First, each of the volcanic centers in Taiwan (namely the Tatun Volcano Group and Kueishantao island but also other offshore sites of past eruptions) is described using volcanological, geophysical and geochemical observations of their past activity and present status. Then, a series of potential hazards is considered along with their impact should an eruption occur in the future. A special mention about the vulnerability of Taiwan’s nuclear power plants to future eruptive activity is also given under the prism of International Atomic Energy Association (hereafter, referred to as IAEA) guidelines for assessing volcanic hazards at nuclear facilities (e.g., McBirney and Godoy 2003). Finally, the existing monitoring and mitigation framework is discussed along with recommendations for strengthening its capabilities in case of a volcanic crisis.

2 Centers of volcanism and their eruptive potential

2.1 Tatun Volcano Group

The Tatun Volcano Group (hereafter called TVG) lies at the northern tip of Taiwan bordering the suburbs of the capital Taipei and includes more than 20 volcanoes, most of

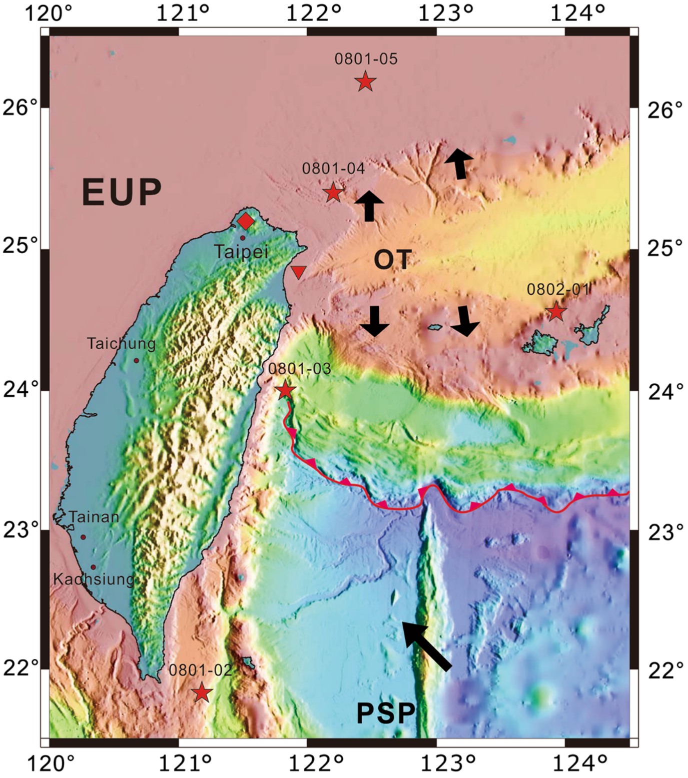

Fig. 1 Map of plate configuration and main volcanic centers in the Taiwan region (*EUP* Eurasian Plate, *PSP* Philippine Sea Plate). The *red curve* delineates the Ryukyu trench where *PSP* subducts beneath *EUP*. *Single arrow* shows the direction of the movement of *PSP* and *double arrows* the direction of extension along the Okinawa Trough (OT). The *diamond symbol* gives the location of the Tatun Volcano Group (TVG) while the *inverted triangle* the location of Kueishantao (KST) island. The *red stars* signify the locations of submarine eruptions as represented in Chen and Shen (2005), and each *number* corresponds to the catalog number of Simkin and Siebert (1994) for each eruption. Also shown are the names and locations of all major cities on the island of Taiwan

which have erupted only once (Wang and Chen 1990). Until some years ago, it was accepted that the last episode of volcanism at TVG occurred at 0.22 Ma, an estimate that was based on K–Ar and Ar–Ar dating of TVG lavas (Tsao 1994) and contributed toward the thinking that TVG is by now extinct. Song et al. (2000) were the first to cast doubt on this assumption by arguing that TVG exhibits many characteristics found in active volcanoes, such as strong hydrothermal activity and mantle-derived Helium detected in fumarolic gases (Yang et al. 1999). The authors also pointed out the inconsistency between the very long time period since the presumably last eruption and the well-preserved edifice of some of the TVG volcanoes, despite the fact that erosion rates in Taiwan are quite high owing to the wet climate. Evidence that the initial estimate for the last eruption at TVG was not accurate was provided by studying more carefully the ash/pumice deposits. Chen and Lin (2002) as well as Chen et al. (2010) collected volcanogenic material from a drilling well in Taipei basin where they found charcoal ash, which was possibly a remnant of forest fires caused by a volcanic eruption. Dating of the organic matter using ^{14}C confirmed that the age of the charcoal is 16.9 ka with an error margin of 150 years. Similar results were obtained from radiocarbon dating of wood buried inside a layer of ash yielding an age of about 13 ka while several other samples gave ages younger than 17 ka (see Belousov et al. 2010). More importantly, there is also evidence that small-scale phreatic explosions occurred about 6 ka near the most well-preserved edifice in TVG, namely that of Mt Chihsinshan (Belousov et al. 2010). Additionally, very recent results point to ages of lava samples from other TVG volcanoes (Shamao, Huangzuei) between 70 and 30 ka (Zellmer et al. 2015), much lower than the initial estimate of Tsao (1994).

Until ten years ago, very little was known about the quantitative and qualitative characteristics of the seismicity in the area of TVG, mostly owing to the small magnitude of the earthquakes and the lack of nearby stations to record them. This situation changed in 2003 when a local seismic network of eight stations was installed in the TVG area and monitoring of the earthquake activity became more effective. Detailed analysis of the seismic data revealed the existence of substantial earthquake activity at shallow depths (<6 km) and of local magnitude equal to three or less (Lin et al. 2005; Konstantinou et al. 2007; Rontogianni et al. 2012). Most of these earthquakes were located in areas of strong hydrothermal activity (Mt Chihsinshan, Tayiokeng) and represent the brittle failure of rock as a response either to increasing fluid pressure, or to the regional stress field (Konstantinou et al. 2009; Fig. 2). Additionally, several other seismic signals were also detected that can be interpreted as the oscillatory motion of fluid inside cracks and/or cavities. These signals were long coda events (also known as “Tornillos”) as well as other low-frequency earthquakes that are also observed in active volcanoes worldwide (e.g., Chouet 1996).

Systematic geochemical monitoring of the gas composition and hot spring water temperature in TVG has started roughly at the same time with the seismic monitoring (Lan et al. 2007; Lee et al. 2008; Yang et al. 2011). Rontogianni et al. (2012) compared the available hydrological, seismic and geochemical observations for the period between 2003 and 2007 in an effort to understand how all these parameters vary as a function of time and how they may affect each other. The observed seismicity varied considerably ranging from 10 to over 50 located events every month. The observed variation most likely was connected to variable fluid pressure levels within the volcano-hydrothermal system. A significant anomaly in the gas composition and high spring water temperature during April 2006 coincided with increased seismicity that started with an earthquake of local magnitude 3.4, which was located near Mt Chihsinshan. The source mechanism of this earthquake was consistent with that of a crack opening rather than shear movement of two fault blocks, while its hypocentral depth of 6 km makes this event one of the deepest in TVG (cf. Fig. 2). Rontogianni et al. (2012) argued that its characteristics and occurrence along with the gas composition anomalies signified the injection of magmatic fluids into the shallow hydrothermal system of the volcano. More recently, Murase et al. (2014) published their results of a precise leveling survey that was conducted in TVG. The authors suggest the existence of two spherical pressure sources in the upper 2 km beneath the Tayiokeng fumarole that may represent hydrothermal reservoirs accepting fluids from deeper sources in agreement with the conclusions of Rontogianni et al. (2012).

In conclusion, based on a series of volcanological, geophysical and geochemical observations, TVG cannot be considered an extinct volcanic center as it was a few years ago. The best-case scenario of future eruptive activity at TVG points to an eruption that will be mildly explosive and will eject only a small fraction of pyroclastic material (Song et al. 2000; Belousov et al. 2010). This activity may be of vulcanian type and would only affect a limited area around the erupting vent through the ejection of ballistic projectiles. However, there is also evidence that Mt Chihsinshan had experienced in the past phreatic

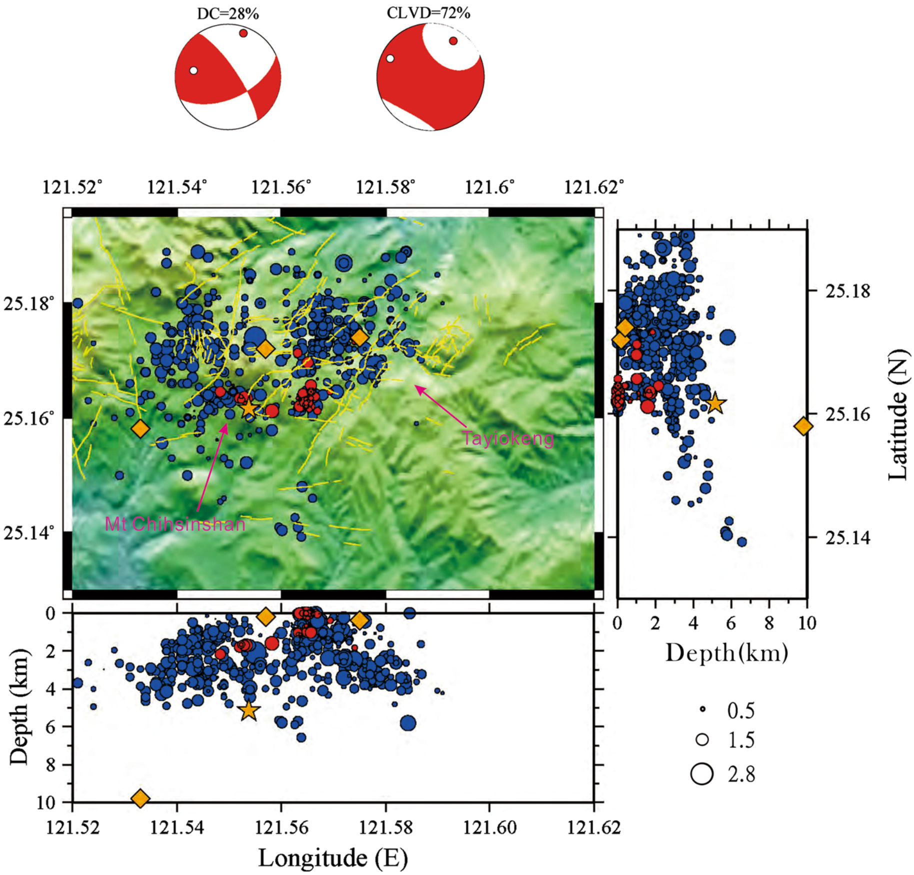

Fig. 2 Map showing the locations of seismic events that occurred during the period 2003–2007 at Mt Chihsinshan and the Tayiokeng hydrothermal area (after Rontogianni et al. 2012). The *blue circles* represent high-frequency earthquakes caused by brittle failure of rock; the *orange diamonds* are low-frequency events caused by fluid movement inside cracks/cavities; and the *red circles* are earthquakes that occurred very closely in time as a response to fluid pressure variations. The *star* signifies the location of the largest earthquake that occurred during the study period in 24 April 2006 while the double-couple (DC) and compensated linear vertical dipole (CLVD) part of its source mechanism is also shown at the top. Each *circle* is proportional to the magnitude of the event according to the scale shown at the lower right part of the plot. The yellow lines represent surface fractures in the TVG area derived from LiDAR data (after Konstantinou et al. 2009)

as well as more explosive Plinian-type eruptions that could affect a much wider area by releasing a considerable amount of ash and pyroclastic material in the atmosphere (cf. Belousov et al. 2010). This would be the worst-case scenario as it would affect a much broader area over northern Taiwan.

2.2 Kueishantao island

Kueishantao island (hereafter called KST) lies offshore NE Taiwan at a distance of about 10 km from the Ilan plain and is a young stratovolcano with many submarine hydrothermal vents that emit high-temperature fluids discoloring the seawater around the island (Fig. 3).

Unlike TVG, whose status as an active volcano had been previously debated, the last eruption of KST was dated at 7 ka (Chen et al. 2001), and therefore, the fact that it is an active but presently dormant volcano was never challenged. An analysis of the geomorphology and volcanic geology of KST reveals that the main edifice lies at the center of the island and has an altitude of 401 m, while the volcanic rocks consist mostly of basaltic andesite along with deposited pyroclastic and lahar material (Chiu et al. 2010). The hydrothermal fluids emanating from the submarine vents have been analyzed, and their geochemical composition showed two important characteristics. First, that the ratio ^{3}He/^{4}He of the gas bubbles is the highest (7.3–8.4) reported for hydrothermally active areas in the western Pacific region (Yang et al. 2005). This implies that the fluids emitted have a significant mantle component, a characteristic that can be interpreted as evidence for a magma chamber beneath KST. Second, hydrothermal fluids are very acidic with pH values as low as 1.52 among the lowest levels found in similar settings (Chen et al. 2005). Regional seismic tomography also provides evidence for a deep (>20 km) magmatic body beneath NE Taiwan that is probably providing the KST volcanic system with melt (Lin et al. 2004).

Despite all these signs of a strong hydrothermal activity that is influenced by deeper magmatic sources, KST has been studied much less than TVG owing to the fact that the island is uninhabited and can be accessed only by boat. Consequently, even though the seismicity levels around KST had been known to be high from previous short-term seismic surveys (Yeh et al. 1989), there was no detailed analysis of the earthquake activity for longer periods due to lack of observational data. This situation changed in early 2008 when a local seismic network consisting of 16 three-component seismometers was installed both on KST and along the Ilan coast (Konstantinou et al. 2013). An analysis of 1 year worth of data revealed that most earthquakes are located to the NE of KST at depths between 2.5 and 10 km (Fig. 3). As in the case of TVG, the largest earthquake (moment magnitude 3.8) exhibited abnormally low-frequency content (<5 Hz) and a source mechanism consistent with that of a crack opening, signifying a volcanic origin. It was followed by numerous smaller events, some of which exhibited also low-frequency characteristics. Unfortunately, these interesting observations could not be correlated with other parameters, such as gas composition variations which could give additional evidence of the possible injection of magmatic fluids in the shallow hydrothermal system of the volcano.

Nevertheless, KST is an active and presently dormant volcano, which exhibits strong hydrothermal activity and high levels of seismicity, mostly with events of small magnitude (<4). As noted by Chiu et al. (2010), past eruptions of KST were found to be predominantly subaerial with lava effusion as their main characteristic; therefore, a future eruption may be of a similar type and only mildly explosive. The lack of any sign of underwater eruptions in the form of pillow lavas, pillow breccias or hyaloclastites should, however, be viewed with caution. This is because previous eruptions within the Holocene or prior to that period occurred under different sea level conditions. On these grounds, the possibility of a future underwater eruption that will involve the explosive mixing of magma with seawater cannot be excluded.

2.3 Submarine volcanic centers

Except from the two well-known volcanic centers with activity during the Holocene, there is evidence for historical eruptions at several locations offshore Taiwan (Simkin and Siebert 1994). Chen and Shen (2005) re-examined all the original historical sources within the last 150 years written in four different languages (English, French, German and

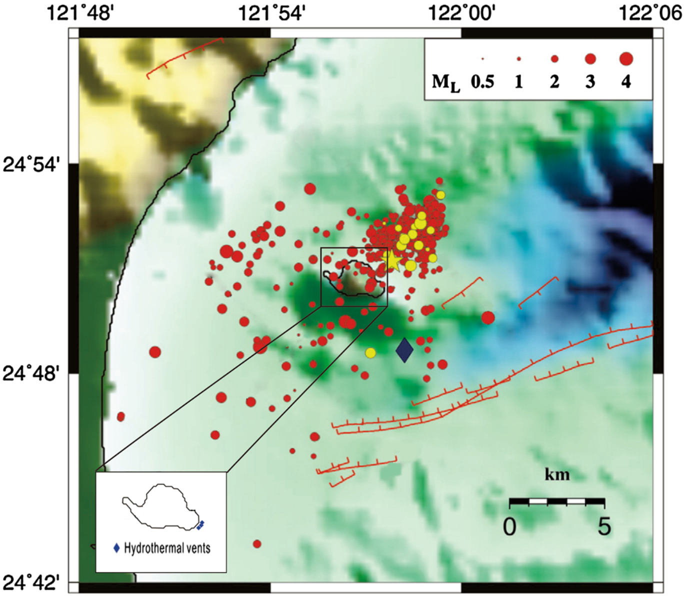

Fig. 3 Map of earthquake locations for events that occurred at or near KST island during the period January–December 2008 (after Konstantinou et al. 2013). *Red circles* represent high-frequency events caused by brittle failure of rock, while *yellow circles* are low-frequency events caused by fluid movement inside cracks following the largest event (local magnitude 4.4) recorded that is shown as a *yellow star*. The *diamond* represents one low-frequency event that occurred prior to the largest event. The size of each *circle* corresponds to local magnitude based on the scale given at the *upper right corner* of the plot. The *inset map* shows the outline of KST island and the locations of the submarine hydrothermal vents near its shores (after Chen et al. 2005)

Japanese). These sources described signs of offshore volcanic activity and were cross-checked in order to clarify their reliability and assign a Volcanic Explosivity Index (VEI; Newhall and Self 1982) as a measure of the strength of each eruption whenever possible. The authors' examination revealed five such eruptions, of which four can be considered as "confirmed" and one of them as "uncertain" due to contradictory information about its location contained in a number of sources (eruption 0801-02 Fig. 1). Most of these eruptions were described in association with phenomena such as steam eruptions, columns of smoke or pumice rafts floating on the sea surface. The VEI of two confirmed eruptions ranged from 0 (eruption 0801-05) to a VEI of 2 (eruption 0801-01). The confirmation of submarine volcanic activity offshore the coast of Taiwan underscores the fact that volcanic hazards may also originate from centers other than TVG and KST.

3 Probability of repose interval exceedance and hazard rates

The question of what is the probability for renewed explosive activity at a volcano, which has not erupted perhaps for thousands of years, is a crucial topic in assessing volcanic hazards and vulnerability. Connor et al. (2006) considered this question by investigating the empirical survivor function of repose intervals of Holocene (last 10,000 years) eruptions for VEI equal to 4, 5 and 6–7, respectively. The authors found that the commonly used in hazard analysis Poissonian model was actually a poor fit to the observed distributions. Instead, the log-logistic distribution exhibited a much better fit, and the survivor function for repose eruption intervals is given by

$$P(T) = 1/1 + (\alpha T)^{\beta} \tag{1}$$

where T is the repose interval and α, β are constants that are estimated after fitting Eq. 1 to the observations. The authors also defined the hazard rate function (the function that gives the probability that a volcano will erupt given that it has stayed dormant until time T) which is

$$H(T) = \beta T^{\beta-1}\alpha^{\beta}/1 + (\alpha T)^{\beta} \tag{2}$$

These equations are utilized in the present study in order to quantify the annual probability of exceedance for the repose interval of the volcanic centers in Taiwan and the corresponding hazard rates. This is done by assuming that the next explosive eruption will have VEI = 4 and the reasons behind this choice are the following: (a) An eruption of this strength is likely to affect areas much broader than the surroundings of the volcano; (b) the fit of the log-logistic distribution is much better for this class of eruptions due to the fact that they were the most numerous in the catalog of Connor et al. (2006); and (c) it is possible that the last explosive eruption at TVG had a similar VEI estimate (Belousov et al. 2010). For the distribution of eruptions with VEI = 4, the constants along with their standard errors were $\alpha = 0.019 \pm 0.003$ and $\beta = 0.765 \pm 0.045$ and these values were adopted here. Table 1 summarizes the results of these calculations for each volcanic center (TVG, KST) and each of the submarine eruptions assuming a repose interval equal to the time since the last confirmed eruption. It can be clearly seen that the probability of exceeding a small repose interval is the highest (e.g., for 90 years $P = 0.365$–0.434) while the annual hazard rate is also the largest. On the other hand, for TVG and KST where the repose interval is thousands of years, the probabilities of exceedance are much lower (<0.036) accompanied by smaller but not negligible hazard rates ($\sim 10^{-5}$). This last point will be discussed in more detail in relation to the risk posed to sensitive infrastructure such as nuclear power plants.

4 Types of volcanic hazards

4.1 Airfall tephra

Tephra is the product of volcanic rock fragmentation, which in turn is the result of magma erupting explosively rather than effusively. The fragmented material, which may have a wide range of particle size from ash size (<2 mm) to block size (>64 mm), leaves the vent and entrains ambient air rapidly. The entrained air is heated, and this is causing the creation of a thermally buoyant plume that rises into the atmosphere until it reaches air of the same density where it spreads laterally in the downwind direction (Parfitt and Wilson 2008). The spatial extent of tephra dispersal is then dependent on a number of factors such as particle size, density, wind and eruption column height. An explosive eruption of this kind can be considered plausible for either TVG (originating at Mt Chihsinshan) or KST, and the tephra dispersal could potentially affect broad areas of Taiwan. The first category of hazards related to tephra transportation and dispersal has to do with damages incurred to electrical equipment, since ash is abrasive and functions as a thermal insulator causing

Table 1 Summary of probabilistic hazard calculations for each volcanic center in Taiwan based on the repose interval T of the last eruption

Volcanic center	T (years)	$P(+1\sigma)$	$P(-1\sigma)$	$H(+1\sigma)$	$H(-1\sigma)$
TVG	6,000	0.018	0.036	6.41×10^{-5}	3.63×10^{-5}
KST	7,000	0.016	0.032	5.50×10^{-5}	3.12×10^{-5}
0802-01	90	0.365	0.434	0.0027	0.0014
0801-05	98	0.349	0.419	0.0026	0.0013
0801-04	147	0.278	0.350	0.0019	1×10^{-4}
0801-03	161	0.264	0.335	0.0017	9.32×10^{-4}

P signifies the probability of exceedance of the repose interval, while H is the hazard rate. σ refers to the standard error of the α, β parameters (see text for more details). The numbers 0802-01, -05, -04 and -03 refer to confirmed submarine eruptions offshore Taiwan

overheating. For an advanced technological city such as Taipei where numerous electronic devices are in use, or there is infrastructure that depends on these (e.g., high-speed railway), this is a hazard that can hardly be ignored. The second category of hazards is related to the fact that ash can pollute water supplies and cultivated land. In the case of Taipei city, water supplies come from the nearby (~25 km) Feitsui dam, which is likely to be affected by ash dispersal as well. Finally, the third category of hazards has to do with aviation and the operation of main airports during the eruption period. It is well-known that jet engines can get clogged by sucking ash particles eventually leading to engine failure (Casadevall 1992). Additionally, the exterior of airplanes that fly through ash clouds can get severely damaged by the abrasive power of the ash particles. Similar to the 2010 Eyjafjallajökull eruption in Iceland, such a situation implies halting of all air traffic at least above northern Taiwan's airspace and the closing of airports for as long as the suspended ash levels are considered dangerous for engine operation. Except from the inconvenience experienced by a large number of travelers, the economic losses from such a scenario are expected to be significant. Previous experience shows that hazards to airports due to ashfall can be of the form of loss of visibility, slippery runways and damage to buildings and parked airplanes (Guffanti et al. 2009). In the area of northern Taiwan, there are two international airports, namely the Songshan airport situated in downtown Taipei and the Taoyuan airport about 40 km from the city center. Both of them are likely to be affected by the ash cloud especially in the case where the eruption originates at TVG.

4.2 Pyroclastic flows

Pyroclastic flows are the result of the collapse of explosive eruption columns, the disintegration of the front part of lava flows, or the destabilization and collapse of lava domes. They consist of hot gas and rock particles (in most cases in the form of ash), and they behave as dense avalanches that can travel at great distances with speeds that may exceed 100 km/h. Pyroclastic flows are very dangerous and destructive phenomena causing the deposition of large volumes of unconsolidated material in broad areas around the volcanic edifice. There is evidence for small-scale pyroclastic deposits in TVG around Mt Chihsinshan that probably correspond to vulcanian eruptive activity during the late Pleistocene (Belousov et al. 2010). Recently, Tsai et al. (2010) produced a volcanic hazard zonation map for the area around TVG assuming an explosive eruption originating at Mt Chihsinshan and that the volume of erupted material was of the order of 1 km^3 (Fig. 4). In this scenario, the pyroclastic flows that will be created will emanate radially from the Chihsinshan edifice and will travel down the valleys up to a distance of about 2 km without reaching the densely populated suburbs of Taipei. Also, pyroclastic flows have been found at KST island even though their deposition characteristics and conditions of emplacement have not been studied in detail. A small (VEI = 3) eruption at KST is unlikely to create pyroclastic flows that can affect mainland Taiwan. However, this is not the case for a larger eruption where these flows under favorable conditions (high temperature and poor size sorting) can travel over the surface of the sea in a manner similar to the 1883 Krakatau eruption (Freundt 2003) and hit the populated Ilan plain that lies a few kilometers to the west of KST.

4.3 Lava flows

The way in which erupting lava flows depends on the chemical and physical characteristics of the magma. In general, low in silica magma (basalts, andesites) results in lava flows that have low viscosity and can move easily without any explosive activity. On the contrary, if the magma is rich in silica (dacites, rhyolites), lava flows have high viscosity and tend to form thick lobes or domes whose emplacement is often accompanied by explosive activity. From the hazards point of view, lava flows travel more slowly than pyroclastic flows and affect much smaller areas around the volcanic edifice. Several lava flows can be found in the TVG area with lengths between 1 and 5.6 km and thickness in the range of 80 and 150 m (Belousov et al. 2010). These represent mostly blocky andesitic lava flows with high viscosity (10^9–10^{11} Pa s) and yield strengths ($>10^5$ Pa). In the hazard scenario of Tsai et al. (2010) mentioned previously, lava flows will follow the same paths with the pyroclastic flows from Mt Chihsinshan to a distance of 2 km without posing any danger to populated areas (cf. Fig. 4). However, two points should be noted here: (a) Lava flows longer than the ones erupted previously may represent a substantial hazard for Taipei city, and (b) even if lava flows are not long enough, they may still cause forest fires as well as the destruction of roads or power lines that will be on their path.

4.4 Landslides and volcanic debris avalanches

Gravitational movements at volcanoes in the form of landslides or volcanic debris avalanches are frequent phenomena and occur due to a combination of factors such as steep slopes, hydrothermal weakening of edifices as well as disturbances such as strong shaking caused by earthquakes and ground deformation. Several volcanic edifices in the TVG area have experienced gravitational mass movements, the largest of them involving a material volume of 0.1 km^3 (Fig. 5). The latest of these has occurred at Mt Chihsinshan where it took the form of numerous retrogressive landslide blocks, partially transformed into a debris avalanche (Belousov et al. 2010). The cause of these mass movements is primarily hydrothermal alteration of rocks, eventually leading to weakening of the edifice without excluding the possibility that strong earthquake shaking might have also played some role. The extent of these landslides/debris avalanches as seen on the map appears relatively limited, even though the deposits of Siaoguanyin avalanche have reached the borders of the Taipei basin. It is also evident from Fig. 5 that only part of Mt Datun has collapsed and that a linear fracture clearly appears to continue southwestwards, suggesting that a new debris avalanche may occur in the future. Therefore, the hazard related to gravitational mass movements at TVG is significant, notwithstanding that such a movement could be caused by earthquake shaking and in the absence of any eruptive activity. Such a situation would pose a significant danger to the numerous visitors of the scenic Yangmingshan National Park, which includes the TVG area.

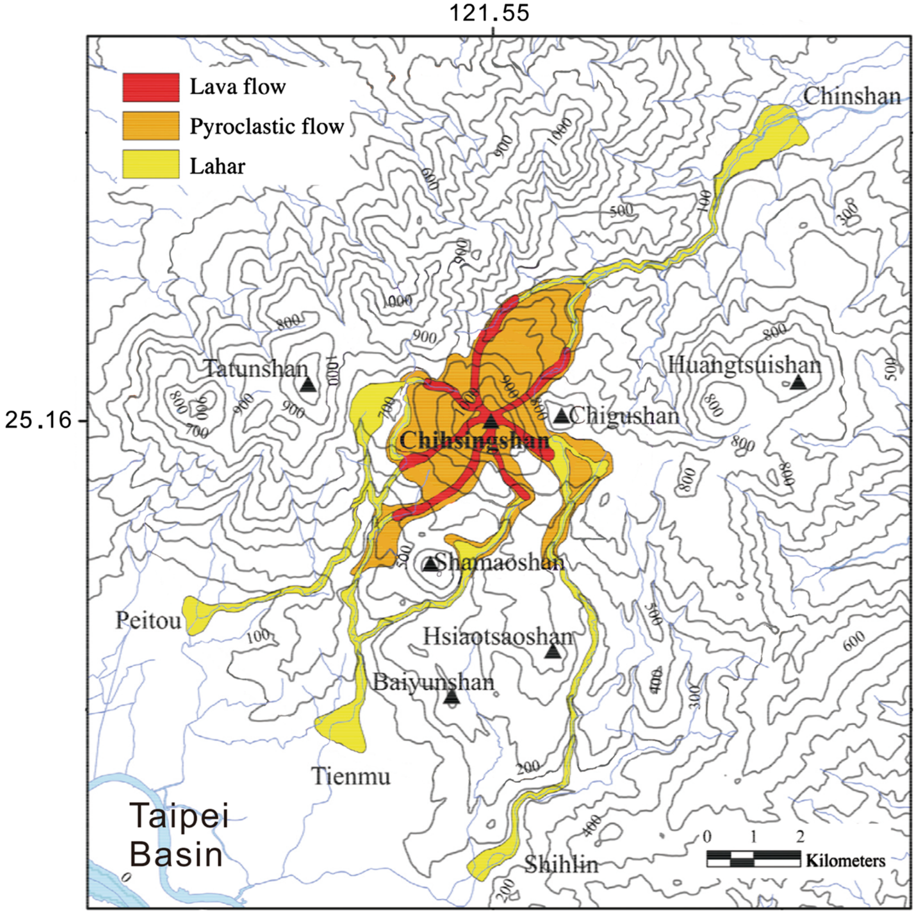

Fig. 4 Map presenting the extent of eruptive products based on observations of past deposits, assuming that the eruptive center is at Mt Chihsinshan (after Tsai et al. 2010). *Black triangles* highlight the peaks of the other volcanic edifices in TVG. Peitou, Tienmou and Shihlin are three of Taipei's densely populated suburbs that border the TVG area

4.5 Lahars

Lahar is the Indonesian word for mudflow, which is a slurry composed of water and volcanic rock particles. If the particle size is that of volcanic ash, then the lahar that will be produced will have the consistency similar to wet concrete. However, lahars may also contain a broad range of particle sizes up to blocks of several meters large which can of course be extremely destructive. As a volcanic hazard, lahars can be considered as a secondary hazard that occurs after the deposition of erupted material days, weeks or years following a volcanic eruption. The existence of thick lahar deposits ($\sim$100–250 m) in the Taipei basin has been confirmed by Tsao et al. (2001) as well as Song et al. (2007) after examining several deep drilling cores. Based on the scenario of Tsai et al. (2010), lahar flows seem to be one of the most significant hazards for Taipei city, as they tend to follow the valleys that lead to densely populated suburbs such as Peitou, Tienmu and Shilin (cf. Fig. 4).

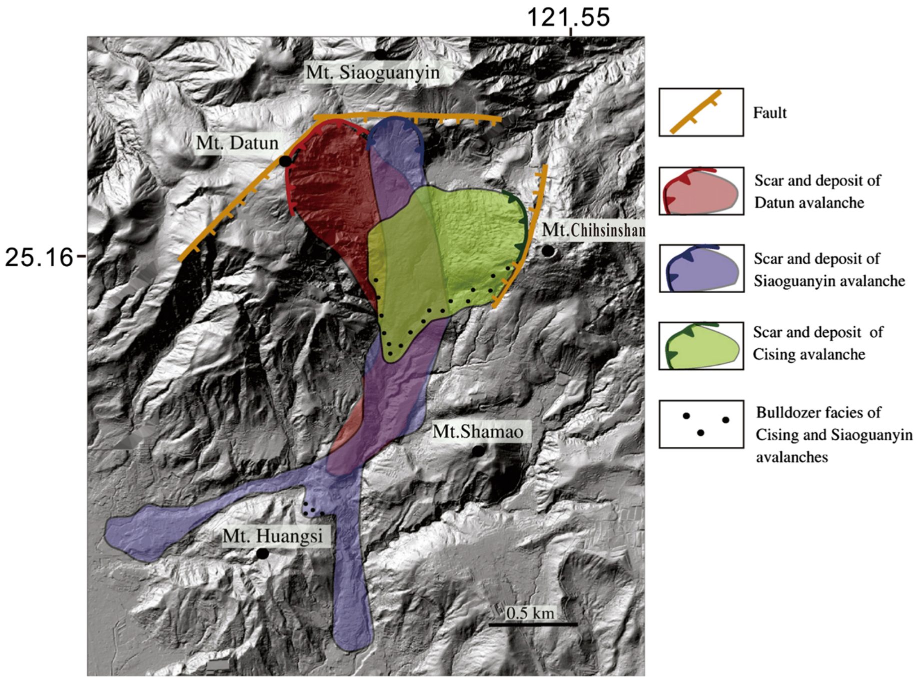

Fig. 5 Extent of previous landslides/volcanic debris avalanches that have occurred at TVG superimposed on a *shaded* topography of the area (after Belousov et al. 2010). The description of each deposit is given at the *right-hand side* of the plot

4.6 Phreatic explosions

The interaction of water with rock that is heated by magma, or with still-hot volcanic deposits has the consequence that water may be rapidly heated and flash to steam. This process in turn causes a sudden volumetric increase within a confined space, finally leading to a phreatic explosion. Belousov et al. (2010) found several small explosive craters with diameters of up to 170 m located along two prominent fissures that dissect the summit of Mt Chihsinshan. The authors suggest that these explosions were not of hydrothermal origin, since the ejected breccias did not contain significant amounts of hydrothermally altered rocks. It is therefore more likely that the explosions occurred when fissure opening caused rapid lithostatic unloading of vesicular rocks of the youngest lava flow of Mt Chihsinshan while this was still hot. Such explosions can pose a significant hazard to the area nearby Mt Chihsinshan while they may occur even without the presence of volcanic activity.

4.7 Tsunami

Tsunami is the Japanese word for harbor waves and is used to describe long-period water waves generated by a sudden displacement of the water column. Such a displacement can be caused either by co-seismic fault movement of the seafloor or may have volcanic origins when part of the energy released during an eruption is transmitted to the sea (Begét 2000). Paris et al. (2014) have recognized five processes that may cause a volcanogenic tsunami:

(a) an underwater explosion, (b) shock waves from an explosion that are coupled to the sea, (c) a pyroclastic flow whose dense part move in the sea, (d) a caldera collapse and (e) subaerial or submarine failure of the volcano edifice. The authors also note that of these processes only edifice failure can produce volumes of material large enough (>1 km^3) to cause a tsunami with wave height more than 3 m. In Taiwan, this kind of volcanogenic tsunami hazard may originate at KST island after an eruption or strong earthquake causes the destabilization of its edifice. There is evidence that KST suffered in the past an edifice failure as shown by a relic landform of a landslide on the northeastern part of the island (Chiu et al. 2010). The tsunami that will be caused by a similar edifice failure in the future would impact the nearby coast of the Ilan Plain whose low relief topography makes it a suitable place for deep penetration of the tsunami waves inland. It is interesting to note that the submarine eruption 0801-03 might have also caused a tsunami, which based on historical records inundated the eastern coast of Taiwan (Lau et al. 2010), even though the certainty of its occurrence is debated.

5 Vulnerability of nuclear power plants

The recognition of the fact that volcanic activity can pose a significant threat to nuclear power plants has led IAEA (2012) to issue specific guidelines for assessing the corresponding hazards. The starting point of such an assessment is the notion of a capable volcano which is defined as "*a volcano that has a significant probability of future activity during the lifetime of a nuclear power plant.*" A set of hierarchical criteria is then used in order to determine whether the volcano is capable or not. These criteria in order of importance are: (1) record of historical activity, (2) surface or subsurface manifestations of magmatic activity, (3) evidence that the time elapsed since the last volcanic activity is less than the maximum repose interval for that specific volcano, and (4) evidence that the time elapsed since the last activity is less than the extreme repose interval for volcanoes of the same type and geological setting. Once the volcano has been determined as capable, an investigation of the potential volcanic hazards that may affect the nuclear power plant can be initiated.

Taiwan presently has three nuclear power plants in operation while the construction of a forth one in the Gongliao area has been halted after fierce demonstrations from anti-nuclear protesters in April 2014 (Fig. 6). Two of the operating plants are within 20 km from TVG and may be affected by volcanic activity; these are the Jinshan and the Kuosheng plant, which is also the largest. Based on the IAEA guidelines, both TVG and KST can be considered as capable volcanoes, despite the lack of historical eruptions, mainly on the grounds of geophysical and geochemical evidence for magmatic activity at depth (cf. Sects. 2.1, 2.2). It should be stressed that for critical facilities such as nuclear power plants, the annual probability of a future eruption near the site must be within 10^{-8} to 10^{-6} in order to be deemed acceptable (McBirney et al. 2003). The annual hazard rates that have been calculated earlier for TVG, KST and submarine volcanic centers are clearly higher than these required levels.

IAEA (2012) has categorized volcanic hazards into two groups, namely the ones that can be remedied to some extent by engineering solutions (ballistic ejecta, ashfall, corrosion by acidic gases, seismic activity, tsunami) and those that cannot (pyroclastic flows, lava flows, landslides, debris flows). Two of these hazards (ballistic ejecta and corrosion by acidic gases) are unlikely to cause any problems in case of an eruption due to the fact that they can affect only areas within a few kilometers from the volcano. Taiwan is also prone to seismic activity of tectonic origin, and consequently, such facilities have been constructed to withstand strong ground motion (acceleration of the order of 0.3 g); therefore, any earthquakes that may accompany the eruption are also unlikely to cause significant damage to the power plants. In the aftermath of the Fukushima disaster, the Taiwanese government stepped up its efforts to improve the protection of the operating nuclear power plants against a potential tsunami, also holding a drill in September 2012 simulating a situation similar to the Fukushima accident. The effects of any of the other volcanic hazards to the safe operation of the plants have not been considered to-date nor how such effects can be minimized. Ashfall hazard, for example, can cause power loss to the plants through damage to the power lines and the backup generators. Accumulated ash may additionally cause blockage of water circulation systems as well as damage through mechanical and chemical effects to the plants' ventilation systems. Lava flow is another likely hazard to the two nuclear power plants nearest to TVG, all the more because a lava flow from a past eruption was found to have stopped only 2 km away from the site of the Kuosheng plant (Belousov et al. 2010).

6 Volcanic risk mitigation

Volcanic risk can be defined as the product of volcanic hazard and vulnerability of the different elements that are at risk (UNDRO 1979). Volcanic hazard can be quantified as the probability of occurrence of a potentially damaging volcanic event within a specific period of time in a given area. On the other hand, vulnerability is related to the degree of loss to a given element that is at risk when a given volcanic event occurs. In this sense, the term "elements at risk" may refer to the population, infrastructure, critical facilities or economic activities within the area affected by volcanism (e.g., Jaquet and Carniel 2006). From this description, it is clear that in the case of Taiwan while the volcanic hazard in terms of probabilities may be low (in fact much lower than the corresponding seismic hazard or hazards related to weather phenomena), the vulnerability to future volcanic activity is quite high, resulting in a level of volcanic risk that cannot be ignored.

Mitigation of volcanic risk can be achieved by a co-ordinated program that will focus on the assessment of potential volcanic hazards, continuous monitoring of volcanic centers, engineering means of minimizing vulnerability and education of the population about volcanoes. More specifically, the aforementioned suggestions should be realized in conjunction with the following actions:

- More detailed studies of the magnitude, style and products of previous eruptions at TVG and especially at KST island are needed, along with accurate dating of these eruptions. Using the constraints from these observations, it will be possible (a) to perform numerical modeling of the spatial distribution of ash or the path of pyroclastic/debris flows and lahars and (b) to obtain probabilistic estimates for the occurrence of each hazard. Tsunami simulations should also be performed considering different scenarios as that of a flank failure and submarine explosion.
- The level of monitoring for TVG can be viewed as quite satisfactory since there is a fully functional seismic network installed in the area and consisting of three-component short-period and broad-band instruments. Additionally, four permanent GPS stations have been installed around Mt Chihsinshan in order to detect any aseismic deformation, and recently, a station that is monitoring soil radon flux has been set up (Yang et al. 2011). However, the situation at KST is completely different with only 2–3 seismic

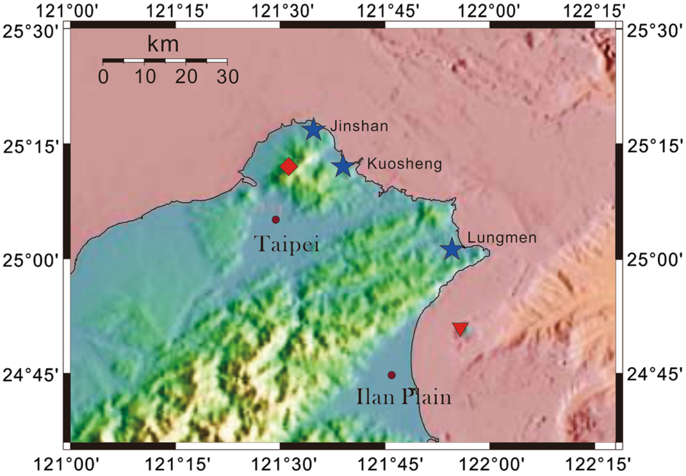

Fig. 6 Map of northern Taiwan highlighting the locations of the three nuclear power plants (*blue stars*) relative to the volcanic centers of TVG and KST (symbols are the same as in Fig. 1). The construction of the Lungmen plant in the Gongliao area has been suspended after anti-nuclear power demonstrations in April 2014. The location of the forth nuclear power plant (the Maanshan plant) is at the Pingtung peninsula in the southern tip of Taiwan

stations installed on the island while the remaining ones are distributed several kilometers away along the Ilan coast. Presently, there is neither GPS coverage on KST, nor fluid geochemistry monitoring which could provide valuable insights during periods of volcanic crises, and this situation should be rectified in the future. The recent establishment of the Taiwan Volcano Observatory (TVO) in October 2011 was indeed a significant step toward an integrated monitoring of Taiwan's volcanic centers, provided that it will be adequately funded and staffed with scientists experienced in volcano monitoring.

- As noted previously, some of the problems caused by volcanic phenomena can be minimized by taking appropriate engineering measures. One notable example is the protection against ash for electrical/electronic devices that control the function of the metro system in Taipei (part of it is above ground) or the high-speed railway. More importantly, the scenario of ashfall affecting the operation of the nuclear power plants should be seriously considered by their operator. Another example is taking measures against a potentially destructive lahar or debris flow in the populated areas of Shilin, Tienmu and Peitou that can be achieved by a combination of engineering solutions and land use considerations.
- The education of the public (and especially those who live very near TVG and KST) on how volcanoes work and what are the hazards stemming from their activity should also be a high priority. Schools can become a focal point for such an effort as teachers, children and their parents can become acquainted with the subject. Such an approach has already been tested successfully in Taiwanese schools regarding seismic phenomena and actions that need to be taken after earthquake early warning (W-T Liang pers. comm. 2014).

It should never be overlooked that risk mitigation lies at the interface between science and political decision making. This omnipresent fact has been vividly highlighted during the 2010 eruption of Eyjafjallajökull volcano in Iceland and the subsequent crisis that developed in the UK after all major airports had to shut down due to the suspended ash. Donovan and Oppenheimer (2012) noted that a key element in the crisis was the absence from the part of the UK government of any contingency plans regarding such a situation which the government had considered unlikely to happen. The slow response to the crisis due to bureaucratic complications was also another problem, as well as the lack of a panel of experts that could have advised the government in time. This lack of hindsight might not seem at first unreasonable, as the UK does not have any active volcano in or near its mainland territory. However, volcanologists know all too well the effects of past Icelandic volcanism (e.g., 1783 Laki eruption) on the British Isles, and should a panel of experts existed, it would have alerted the government to the threat of suspended ash. The authors finally stress that after this experience, the UK government decided to completely change its attitude and "*…if the risk is very high impact – even if it is unlikely*" to conduct appropriate planning (Donovan and Oppenheimer 2012). The lessons learned from the 2010 ash crisis in the UK should be carefully reviewed by policy makers in Taiwan and consider adopting a similar attitude toward volcanic risk management.

7 Conclusions

In this work, several aspects of hazards stemming from future volcanic activity in Taiwan and corresponding vulnerabilities have been considered and analyzed. The main conclusions can be summarized as follows:

1. TVG and KST islands are the main volcanic centers with a potential to erupt in the future. Evidence for this potential comes from their activity during the Holocene but also from present observations of strong hydrothermal and seismic activity. There are also historical records of submarine volcanic activity offshore the northern and eastern coast of Taiwan within the last 150 years.
2. For a technologically advanced country such as Taiwan, ashfall can be a significant volcanic hazard mostly due to the fact that ash can affect electronic devices and power lines, bring air traffic to a halt and contaminate water resources as well as cultivated land. Other types of volcanic hazards that are relevant owing to the wet climate of Taiwan are lahars and landslides/debris avalanches that have the potential to hit densely populated suburbs of the capital Taipei. Some hazards may occur even without any eruptive activity: A strong regional earthquake can destabilize a volcano edifice causing a landslide, which in turn may decompress the hydrothermal system of the volcano triggering a hydrothermal explosion, or excite a tsunami should the material fall into the sea.
3. The nuclear power plants in Taiwan seem to have sufficient protection against strong ground motion due to earthquakes and tsunami of tectonic or volcanic origin. However, this is not the case for volcanic hazards such as ashfall or lava flows; in this case, engineering solutions can minimize the dangers and should be considered by the plants' operator.
4. There is a general belief that the probability of a future eruption in either TVG or KST is very low; this is only half the truth with the other half being the increased vulnerability that results from the dependence of modern society on technology. Volcanic risk therefore, being the product of volcanic hazard probability and vulnerability, is not insignificant for Taiwan, and every effort should be made in order

to mitigate it as much as possible. Risk mitigation can be effective if scientists and policy makers work together toward this goal.

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