VOLCANIC HAZARD ASSESSMENT IN GEOTHERMAL AREA

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ABSTRACT

Tectonically, most of the Indonesian geothermal areas are located in active volcanic region. The volcanoes may erupt violently causing damages to the power plant site and energy production. In order to minimize loss of live and property damages it is proposed to assess volcanic hazards in geothermal areas. The first step of this study is to collect available information on volcanic phenomena and the rocks in the region. The volcanic phenomena consist of ballistic projectiles, pyroclastic ash-falls, flows, and surges, lava flows, debris avalanches, lahars etc. The result of the data analyses can be used to decide whether a volcanic hazard evaluation is required or not. If it does, it requires identification of all volcanic hazard sources. Data analysis using conservative deterministic evaluation of the effects of volcanic hazard phenomena will yield a screening distance value. If the site is located inside the screening distance value(s), the effects of a particular volcanic hazard must be evaluated. In case the area has historical or Holocene capable volcanic source, Deterministic Evaluation Method is used, or otherwise, Probabilistic Evaluation Method is used when the area has only Pre Holocene capable volcanic source. The result of the evaluation will yield a decision whether the site is accepted or is rejected. When the analysis gives a decision to accept the site, an engineering design base for geothermal power plant construction is derived.

1. INTRODUCTION

Most of the Indonesian geothermal fields are located in active volcanic region. The volcano may erupt destructively causing damages to the power plant site and energy production. This possibility requires a study to minimize loss of live and property damages relating to volcanic disasters in the geothermal areas. A similar study has been promoted by The International Atomic Energy Agency (IAEA, 1997) for new nuclear power plant sites in volcanic region.

The aim of this paper is to propose a guidance on the criteria and methods for evaluation of a site for a geothermal power plant with respect to the potential effects of volcanic activity which may jeorpardize its safety. Different types of phenomena associated with volcanism discussed in terms of their influence on site acceptability and on derivation of design basis parameters. This idea is developed for application to new geothermal power plant sites. The guidelines and procedures discussed in this paper can appropriately be used as the basis for the safe siting and design of geothermal power plants in different volcanic environments.

2. TYPES OF VOLCANIC PHENOMENA

Volcanic phenomena that may affect a geothermal site are :

1. ballistic projectiles
2. fallout of pyroclastic material (ash, pumice, scoria, etc.)
3. pyroclastic flows and pyroclastic surges
4. lava flows
5. debris avalanches, landslides and slope failures
6. debris flows, lahars and floods
7. volcanic gases
8. ground deformation
9. earthquakes
10. tsunamis
11. geothermal anomalies
12. ground water anomalies
13. opening of new vents

Each manifestation has a different order of magnitude of critical parameters, such as density, velocity, temperature and area distribution. Ejection of ballistic projectiles such blocks, bombs and other solid fragments are caused by explosions occurring within craters. The solid objects are propelled by high pressure gas and follow ballistic trajectories. The speeds of the projectiles can be more than 300 m/s and the maximum horizontal distances to the impact point can exceed 5 km from the origin. The impact energy of a single projectile may reach 1 Joule. If projectiles at high temperatures fall on vegetation, houses or other flammable structures, they may start fires. Hazard zones associated with ballistic projectiles are normally mapped as concentric circles around existing vents. Radii of hazard zones are determined from the distribution of ballistic projectiles deposited during past eruptive episodes and using probabilistic estimates of eruption energies (Self et al., 1980).

The fall and deposition of volcanic ash can be carried by wind when these particles are propelled by an explosive eruption to an altitude. On falling they normally reach a constant velocity, which is determined by the size, shape and density of the falling particle. Their distribution is governed by the direction and strength of prevailing winds and height of the ash column. If the ash-fall is thick, it may cause serious damage to transportation, agriculture, forests and other social and economic activities. Ash particles drifting in the air sometimes obstruct air traffic by sandblasting the exterior of aircraft and damaging and even stalling jet engines (Casadevall, 1994). By loading the roofs of building, ash accumulation may cause collapse, particularly when the ash becomes soaked by rain. Hazards due to pyroclastic falls are usually determined by mapping past fall deposits, consideration of current wind patterns, and often by computer simulation (e.g. Carey & Sigurdsson, 1982; Suzuki, 1983).

Pyroclastic flows are high-temperature mixture of rock fragments, volcanic gases and air that flow down the slope at high speeds (e.g. Smith, 1960; Sparks et al., 1978; Moore, 1967). Flow velocities reach 10 to 100 m/s making evacuation impossible once a pyroclastic flow has begun (e.g. Bronto et al., 1997). The temperature can be close to that of the original magma or between 300 – 850 ^oC (Fisher & Schmincke, 1984). The volume of solid materials transported by a pyroclastic flow may range from less than 10^5 m^3 to more than 10^{11} m^3, depending on the mode of generation and emplacement. The lower, dense part of the pyroclastic flow deposit may have a bulk density of 0.1-0.5 t/ m^3; the upper dilute cloud has a bulk density close to 0.001 t/ m^3. Owing to their great mass, high temperatures, velocity, and great mobility, pyroclastic flows present serious hazards, including burial, incineration, asphyxiation and impact. Secondary hazards derived from heavy rainfall can generate lahars and floods.

Pyroclastic surges are turbulent, dilute gas-solid suspensions that flow over the ground surface at high velocities with less regard to topography than pyroclastic flows. They can be divided into two types, hot and cold. Hot pyroclastic surges, also known as ground surges, are generated by many of the same processes that form pyroclastic flows and often over-ride or precede pyroclastic flows. Cold pyroclastic surge, also known as base surge, originate from hydromagmatic explosions in which shallow ground water or surface water interacts with magma. They typically contain water or surface water and /or steam and have temperature at or below the boiling point of water. Base surges are generally restricted to a radius of 16 km from the vent. Pyroclastic surges pose a variety of hazards including destruction by ash-laden clouds, impact by rock fragments, and burial. Hot pyroclastic surges present several additional hazards including incineration, toxic gases, and asphyxiation. Hazards associated with pyroclastic flows and surges are evaluated by mapping past deposits, studying their physical volcanology and estimating their temperature of emplacement. Analysis of topography and drainage patterns and computer simulation are also used to estimate hazards associated with these phenomena (Valentine & Wohletz, 1989).

Lava flows are driven by gravity and follow the drainage lines of the topography (Kilburn & Luongo, 1993). They behave like viscous fluids, usually with a semi-solid crust on the surface. The morphology and velocity of lava flows depend on the eruption rate, temperature, composition, vent geometry and topography. Their length can reach tens of kilometers and their thickness from less than 10 m to more than 100 m. The temperatures of lava flows range from 800 ^{o} C to 1200 ^{o} C. The speed of a lava flow is normally low, less than 100 m/day especially for andesitic and dacitic lavas. Hazards associated with lava flows are usually estimated by mapping the distribution of past lava flows, mapping current drainage patterns and related topographic features that would control lava flows, and mapping vents from which lava flows could erupt. Computer simulation of a lava flows has been used to estimate hazards (Barca et al., 1994; Wadge et al., 1994).

Most volcanic edifices are steep-sided and may therefore become unstable as a result of erosion or deformation. Partial or complete failure of the slopes often produces debris avalanches, which are high-speed turbulent flows of rock fragments and entrapped air (Ui, 1983; Siebert, 1984). A large collapse may leave a horse shoe-shaped scarp on the upper part of the slope. Thickness of deposits may reach of several tens of meters and extends tens of kilometers from their origin. The damage caused by a debris avalanche is mainly by physical impact and burial and the devastation in the central part of the flow can be total. Hazards associated with volcanic debris avalanches and related phenomena are estimated by mapping the distribution of these deposits and related facies, such as lahars, in the region of the volcano, and by identifying morphological features which indicate that large scale collapse has occurred in the past. Topography, structural studies of the volcano, and computer analysis of simulated volcano collapse events assist in the estimation of risk at a particular site.

Mixtures of solid volcanic material and water, as well as other rocks, soil and vegetation, frequently form torrents which flow down valleys and river courses whenever abundant surface water is available after heavy rainfall (Johnson, 1970; Rodine & Johnson, 1970). These are called lahars or volcanic debris flows. They grade into flood streams, heavily loaded with suspended sand and clay particles. The dynamic behaviour is dictated mainly by the nature and proportions of material, topography, their dimensions, and weather. Although flow velocities are slower than those of pyroclastic flows, large lahars may travel 50 km or more and have volumes of more than 10^7 m^3. Physical damage caused by volcanic debris flows and lahars may also be comparable to that of their non-volcanic equivalents (Lowe et al., 1986). Mapping of lahar deposits provides one means of evaluating this hazard. However, deposits from extremely destructive lahars are often minimal and may be missed in the geologic record. Lahar hazards are often evaluated by identifying (i) potential source regions for lahars, including crater lakes and seasonally high rainfall; and, (ii) drainage patterns likely to contain lahars and to transport these flows great distances. In the past, geologic mapping of these hazard zones has been highly successful in forecasting the areas impacted by lahars (Hall, 1985; Voight, 1985).

Volatile material exhaled from volcanic vents, solfataras and fumaroles, some of which may be far from an active volcano, may be highly reactive and hazardous to human and property. Although volcanic gases consist mainly of H_2O, they also include CO_2, SO_2, H_2S, CO, Cl, F etc. which in large amount, can have serious health effects. Gases may be discharged in large quantities either from established vents or from new fissures unrelated to established vents, as in the case of Dieng (Java, Indonesia) in 1979, or from crater lake as in the case of Lake Nyos (Cameroon) in 1987. Because these gases are usually heavier than air, they tend to follow drainage systems and collect in topographical depressions. Hazards due to volcanic gases are assessed by mapping hydrothermal manifestations and considering topography, wind and weather patterns.

Volcanic earthquakes usually occur in swarms and have a smaller magnitude than those of tectonic origin. Volcanic tsunamis may be generated when landslides, pyroclastic flows, debris avalanches, and lahars enter the sea or large lakes. These are also set off by the dislocation of the seafloor by offshore volcanic or seismic events. Collapse of a volcanic edifice triggered by volcanic eruptions or earthquakes may lead to large displacement of the slopes, which turn can generate tsunamis. Many of the large historic disasters have been caused by tsunamis directly related to volcanic activity, such as Krakatau (Simkin & Fiske, 1983) and Mt. St. Augustine (Kienle et al., 1987). Hazards due to tsunamis are evaluated based on topography in the site vicinity, distance of the site from large bodies of water and bathymetry.

Increases and fluctuation of ground surface temperature are frequently associated with volcanic activity. Formation of new fumaroles and steaming ground can destroy vegetation, destabilize slopes and cause subsidence. A groundwater system in which the thermal gradient is close to the boiling curve at depth can be destabilized by a large excavation that lowers the combined pressure and impedance of overlying rocks. In some cases, phreatic explosions occur, resulting in the formation of pit craters. Evaluation of hazards due to the presence and development of hydrothermal systems around volcanoes is particularly important when considering calderas and volcanic complexes where hydrothermal systems can extend well beyond the edifice of the volcano. These hazards are often recognized by mapping alteration zones on and around the volcano, measuring soil degassing of ^{222} Rn, He, Hg, CO_2 and related gases, and through the use of geophysical surveys, particularly electrical surveys (Armannsson et al., 1989; Struchio et al., 1988). Drilling provides information on the subsurface extent and temperatures of hydrothermal systems (Goff et al., 1987). Models of multiphase flow and heat transfer in the hydrothermal system may assist in the assessment of how geothermal anomalies will respond to renewed volcanic activity or intrusion of magma (Lichtner, 1985; Manteufel et al., 1992; Nitao & Tough, 1989)).

Deformation driven by gravitational collapse of volcanic slopes, collapse of pit craters and grabens or shallow intrusion of magma are among the typical examples of ground deformation. Horizontal displacements of more than 100 m were produced by the 1977 eruption of Usu volcano in Hokkaido (Japan). Even the slow deformation of slopes may, with time, lead to considerable horizontal and vertical displacement manifested as faults, cracks and undulations of the surface. Significant ground deformation may occur as a result of magma injection during the formation of monogenetic volcanoes (Kuntz et al., 1986).

Volcanic activity, intrusions of dikes and sill, and associated crustal deformation may affect ground water level, and temperature, and alter the discharge of cold and hot springs and geysers. Such changes, if widespread, can affect the regional ground water systems. Techniques used to evaluate groundwater hazards resemble those used to evaluate geothermal anomalies. Groundwater hazards are evaluated using mapping, data from wells, and geophysical surveys. Numerical models of the impact of dike injection of regional groundwater flow have been developed (Ahola & Sagar, 1992).

Explosive eruption of a volcano can generate supersonic shock waves powerful enough to break windows at distances of several kilometers Lightning often accompanies volcanic eruption. Lightning results from charge differences between the erupting column of ash and the atmosphere. In some cases, lightning and high static charges occur up to several kilometers from the erupting volcano.

Volcanic activity in a region can result in the formation of new vents. These may initiate along fissure zones that are up to several kilometers long, but normally eruptive activity localize as the eruption continues, resulting in the formation of cinder cone and tuff rings. Interaction of magma with groundwater results in explosive activity and the formation maars and phreatic pit craters. Eruptions from new vents may last from several hours to years, as occurred during the formation of Paricutin Volcano, between 1943-1952. Where associated with larger volcanic structures, such as shield volcanoes and calderas, new vents often form along rift zones or other major structures on the volcano. New vents also form in volcanic fields that are not associated with larger volcanic structures. Vent distribution within volcanic fields is sometimes partially controlled by regional structure and vents often cluster within volcanic fields. New vents can be the source of significant pyroclastic fall and voluminous lava flows.

3. GENERAL REQUIREMENTS

During the initial stages of the siting investigation, all relevant data should be collected from available sources (publications, technical reports, and related material) in order to identify volcanic phenomena with potentially hazardous effects on the proposed nuclear power plant (see box 1, **Fig. 1**). The nature and amount of information required for an adequate evaluation of volcanic hazards depend mainly on whether active or not active or potentially active volcanoes are present in the site region.

If evidence of historic volcanic activity in this region is found in the available records, a more detailed investigation should be performed to evaluate the volcanic hazard (boxes 2 and 6, **Fig. 1**). Even if no evidence of historic volcanic activity is found, a further investigation of the presence of volcanic rocks should be examined. If no volcanic rocks of Cenozoic age are found, no further volcanological studies are required (boxes 3 and 9, **Fig. 1**). If evidence of Cenozoic volcanism within the region is found, more detailed geological and volcanological information should be collected in order to define more precisely the age of this activity. This is particularly important where reliable age determinations are not already available.

Further investigation should be required if one or both of the following is found :

- evidence of Quaternary volcanism;
- evidence of Pliocene or Quaternary calderas or volcanic fields.

The objective shall be to determine the potential of renewed activity, herein referred to as capability (box 5, **Fig. 1**). All effects of capable volcanoes or volcanic fields, including historically active volcanoes, should be investigated in terms of their impact on the site (box 6, **Fig. 1**). The volcanic hazard evaluation should be proceeded.

Potential effects of volcanism may result in site rejection. If the site is not rejected, the nuclear power plant should be protected from the potential effects of volcanism by either,

(i) providing a safe distance and elevation to the site for the particular volcanic effect, or

(ii) designing the plant to withstand the volcanic effect including all its consequences (boxes 7 and 8, **Fig. 1**).

Under some circumstances it may be advantageous to monitor certain volcanoes throughout the lifetime of the plant in order to forecast their behavior and potential effects on the site. In this case, a monitoring program should be prepared and implemented, preferably in co-ordination with competent specialized agencies in the country.

A quality assurance program should be established and implemented to cover all activities related to data collection, data processing and interpretation, field and laboratory investigations, desk studies and evaluations that are within the scope of this report.

4. NECESSARY INFORMATION AND INVESTIGATION

The validity of any assessment of volcanic hazards is dependent on a sound understanding of, (1) the regional geological and tectonic setting, and (2) the character of each individual eruptive center within the site region. To achieve this level of comprehension, it is necessary to compile integrated information for each of the volcanic provinces in the region. The characteristics of the volcanic province should first be related to the tectonic regime, taking into account both the past evolution of the region and its potential future development. The goal of regional studies is to identify all volcanic phenomena that may impact the site. The regional scale investigation requires a compilation of all available and relevant geological, geophysical and volcanological information for Cenozoic volcanism in the region. All potential sources of volcanic phenomena listed in Table 1 located within this region should be identified. The typical radius of this area should not less than 50 km from the site. This area may not be symmetrical, depending on the geology and physiography of the region. The information obtained in this study should be compiled on maps that are typically on a scale of 1 : 100.000.

The ages of Pliocene and Quaternary volcanic deposits having a regional extent of 100 km2 or more should be defined by appropriate analyses such as stratigraphic methods and radiometric age determination.Volcanic sources should be identified using regional geological data and reconnaissance mapping. These data should be supplemented using isopach maps, distinctive petrographic and geochemical characteristics and topographic features that may influence the distribution of volcanic deposits. Spatial and temporal trends in Pliocene and Quaternary volcanism should be identified. The tectonic setting of Pliocene and Quaternary volcanism should be characterized. Volcanoes and volcanic fields that have been identified in the regional survey as potential hazards to the site should be examined in more detail, as follows:

1. Volcanoes or volcanic fields should be characterized in terms of morphology, eruptive products, and characteristic behavior.
2. The history of each volcanic center should be determined in order to identify its evolutionary stage of development and its potential to generate each of the phenomena.
3. Records of other geologically analogous volcanoes should be used to provide a better perspective of the long term development and possible future activity of the volcano. Information obtained from published and unpublished sources should be augmented by specific studies designed to acquire additional information of potential importance to the site. These studies normally include some combination of the following :
    a. Geological mapping on a scale of 1 : 50,000 or less.
    b. Geophysical surveys, including location of gravity and magnetic anomalies.
    c. Geochemical analysis and petrologic models relating eruptive activity to compositional variations of the magma and the stratigraphic sequence.
    d. Linking stratigraphic sequences and tephrochronology. This may entail both studies of surface exposures and drilling.
    e. Radiometric age determinations of major eruptive units and key stratigraphic markers.

These data will be used to establish the geologic history and structural evolution of the volcano or volcanic field. More detailed investigations should focus on (i) possible hazards originating in the site vicinity, and (ii) local conditions that could influence the impact of more distant events on the site. These studies should encompass the site vicinity (typically up to a radius of 10 km) with the specific objectives of assessing all potential volcanic hazards and delineating their possible influence on maps having a scale of 1 : 10,000 or less. Potential hazards identified in this initial examination should be further analyzed to determine how the local conditions might influence the effects of close and distant events. These conditions include factors such as:

1. meteorological, topographic and hydrologic conditions between the source and the site;
2. geothermal or hydrothermal activity within the site area;
3. man-induced disturbances of the thermal or hydrothermal regime.

5. DETERMINATION OF CAPABILITY OF VOLCANOES

The concept of the capability of a volcano is introduced in order to define the state of a volcanic system and as a means for evaluating its potential reactivation. This section provides guidelines for assessing the capability of a volcano or a volcanic field. The criteria of determining if a volcano or volcanic filed is capable are the following:

1. historical volcanic activity;
2. manifestation of current magmatic activity;
3. indication that the time elapsed since the last volcanic activity of a volcano or volcanic field is not sufficiently long compared with the representative maximum repose interval for that specific volcano or volcanic field;
4. indication that the last volcanic activity occurred more recently than the duration of the 'increased extreme repose interval' for the volcano type.

These criteria are applied in hierarchical manner. If one or more of these criteria are met, then the volcano is considered to be capable. Manifestations of current magmatic activity indicate that a volcano or volcanic field is capable. These include : (1) geothermal activity, (2) ground deformation, and (3) seismic activity.

6. EVALUATION OF VOLCANIC HAZARD

The starting point of a volcanic hazard evaluation is the identification of all capable volcanoes and volcanic fields (Fig.2). Each volcanic source should be evaluated (i) phenomena that can be produced by the source, and (ii) activity history of the source. Volcanic hazard evaluation for capable volcanoes and volcanic fields is based on deterministic and probabilistic methods. For each phenomenon a conservative deterministic evaluation should be made for the purposes of screening. The following assumptions are normally part of this evaluation:

1. An eruption occurs at each volcanic center, field or province at its closest approach to the site.
2. The magnitude and duration are postulated to be the maximum potential eruption for this volcano (data from analogous volcanoes may also be used).
3. It is further postulated that, in relation to the phenomena considered, unfavourable conditions of volcanic source exist which will have the greatest impact on the site. For example :
   a. In the case of pyroclastic fall, the direction of wind directly toward the site at a maximum credible velocity and at the elevation of the densest part of the eruption column for the entire duration of the eruption.
   b. In the case of avalanches, lahars, debris and pyroclastic flows, the source is assumed to be at the highest elevation and to have the greatest possible potential energy. Volumes are assumed to be maximum observed on volcanoes of comparable form and activity.

The result of this evaluation will be a set of areas around the volcano within which the considered phenomenon should be further analyzed. The distance from the source to the boundary of each such area is called screening distance value (SDV) for the particular phenomenon. It follows that volcanic deposits within the site vicinity are direct evidence that the site lies within the SDV for that particular volcanic phenomenon. For phenomena where the site is included within the SDV, further evaluation should be made to establish parameters for and quantity the effects of the phenomena at the site to decide whether or not an engineering solution is feasible to protect the plant from these effects.

Case I – If the volcanic source with which the phenomena is associated is a capable volcano active during the Holocene, then the decision should be made on the preceding deterministic evaluation concerning : (a) acceptability of the site, (b) derivation of engineering design bases for the plant in relation to each phenomenon originating from this source. Holocene volcanoes that have not erupted historically are included in Case I because the Holocene is a sufficiently long period of time compared to the lifetime of the nuclear power plant whereas the length of the historical record varies by country or region. This deterministic evaluation may be made for each volcanic phenomenon individually. Only volcanic phenomenon produced by Holocene eruptions need to be considered deterministically. All other volcanic phenomena should be evaluated probabilistically.

Case II – If the volcanic source with which the phenomenon is associated is not a historical or a Holocene volcano but is postulated to be capable as result of the evaluation of investigations, it is recommended :

1. Using the record of activity of the source or analogous volcanoes, a statistical evaluation should be made to determine spatial and temporal patterns and trends.
2. For each type of phenomenon, a statistical analysis should be performed to determine recurrence rates and/or the probabilities of events having a range of possible severities, and using observations of analogous volcanoes.
3. Decision on the acceptability of the site with respect to each phenomenon should be made on the basis of probabilities associated with each phenomenon. The level of acceptable probability for each phenomenon is a function of its effect on the site. These probability levels should have the same order of magnitude as similar events considered in the external hazard evaluation for the site.
4. If the site is found to be acceptable for all phenomena, the engineering design bases should be derived deterministically.

7. DESIGN CONSIDERATIONS

A combination of deterministic and probabilistic approaches is used to decide whether or not an acceptability problem exists for the site due to volcanic hazard. If it is demonstrated that the plant can be protected from volcanic hazards through design measures only (i.e. the site does not need to be changed), then a set of design basis parameters should be derived to account for all the effects to which the plant may be subjected. Each effect which is included in the design basis values of other external events to the extent possible. For some effects it may be possible to demonstrate that design basis parameters derived for other external events envelope those derived for volcanic hazards (**Table-1**).

8. MONITORING SYSTEMS FOR VOLCANIC ACTIVITY

In some cases, monitoring of capable volcanoes may be useful. If decision is made to monitor the activity of a volcano, the type and extent of monitoring should be selected according to need and on a case-by-case basis. If a volcano is monitored in relation to some effect it may have on the site, consideration should be given to this within the framework of the emergency plan of the geothermal power plant as recommended by the Code. A detailed procedure should be prepared to consider and/or respond to anomalies detected by the monitoring system. If available, close co-operation with existing surveillance systems such as those utilized by national programs for prediction of volcanic eruptions and mitigation of disasters is recommended. Exchange of observational data and consultation with experts in volcanology working in such programs generally provide invaluable benefit. Some monitoring methods are volcanic earthquakes, ground deformation, changes in geomagnetism and geoelectricity, gravity, volcanic gases, geothermal anomaly, cold and hot springs, etc. By repeated visual inspections from a distance or on the volcano close to the crater, it is often possible to detect the first symptoms of change in volcanic activity. Such features include anomalous sounds like rumblings, fluctuations of fumaroles and solfataras, drying up of wells, springs, lakes and vegetation.

9. CONCLUSIONS

1. To support exploration and exploitation of geothermal energy, volcanic hazard assessment in the area is proposed.
2. There are 14 types of potential volcanic hazard that should be evaluated in geothermal areas.
3. All relevant data covering geology, geophysics and geochemistry are required to evaluate the volcanic hazards.

4. Analysis using deterministic evaluation is carried out for historical or Holocene capable volcanic sources, whereas the Pre Holocene ones are approached by probabilistic evaluation.
5. If the geothermal plant can be protected from volcanic hazard through design measures, a set of design basis parameters should be derived.
6. Monitoring of volcanic activity is recommended starting from exploration stage through the live of the geothermal power plant.

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Table-1

Design considerations for volcanic phenomena

Volcanic phenomena	Design considerations
Ballistic projectiles	Ballistic projectiles can be compared with impacts due to tornado-borne missiles or aircraft crashes. In general, it would be expected that geothermal power plants are sited sufficiently far (> 5 km) from the source of ballistic projectiles.
Fallout of pyroclastic materials	Ash-fall is the most widespread phenomenon due to volcanoes. The main parameters for consideration are the expected thickness, particle size and density, and rate of accumulation of ash at the site. Consequences of substantial ash-fall would be the static vertical load on structures, potential blockage of cooling water intake systems and adverse effects on all ventilation systems.
Pyroclastic flows, surges and lava flows	Generally. It is not feasible to protect a geothermal power plant from lava flows, pyroclastic flows or pyroclastic surges by engineering solutions.
Air shocks and volcanic lightning	Air shocks are limited in their radius of influence. In any case, protection against such pressure waves is common for most geothermal power plants because of considerations for external man-induced events, e.g. pipeline accidents, accidents involving transport of explosive material or external natural events, e.g. extreme meteorological phenomena, such as tornadoes. Volcanic lightning is similar to lightning caused by extreme meteorological events. Protection of the plant against volcanic lightning can be achieved by engineering design measures.
Debris avalanches, landslides and slope failures	Debris avalanches should be considered separately from other slope failures mainly because of the very large volume involved and the high velocities of the avalanche. It may not be feasible to provide engineering design to protect the geothermal power plant against this phenomenon. Other, smaller scale slope failures can be treated within the scope of other (i.e. non-volcanic) geotechnical hazards. Decisions on how to protect the plant against these hazards should be made on a case-by-case basis.
Debris flows, lahars and floods	Debris flows, lahars and floods can be considered together with floods of non-volcanic origin. Protection of the plant against these phenomena would normally entail having a 'dry site'. An important difference of these phenomena from ordinary floods is the short time of warning available after the onset of the flow. High flow velocities and high flow volumes should also be expected.
Volcanic gases	The flow paths, types and expected concentrations of gases should be estimated at the site. The methods would be similar to the treatment of hazards from gases originating from man-made sources. The adverse effects of volcanic gases include toxicity and corrosion. Protection of plant personnel should be ascertained through engineering solutions and administrative measures.
Ground deformation	Generally, it is considered that engineering solutions are not feasible to provide protection against large ground deformation.
Earthquakes	The effects of a volcanic earthquake to a geothermal power plant are similar to those of a tectonic earthquake. Therefore, identical methods can be used in their analysis.
Tsunamis	Volcanoes are only one source of tsunamis. These should be considered within the framework of coastal flooding assessment. As in the case of river flooding, the protection of the plant would entail the provision of a 'dry site'.
Geothermal and groundwater anomalies	These should be considered both for their direct effects at the site (i.e. change in the design basis water level) as well as the impact of secondary hazards such as landslides and subsidence. Although minor fluctuations in geothermal and groundwater conditions would be tolerable and protection can be provided through engineering design, extreme cases could be impossible to cope with.
Opening of new vents	Generally, it is considered that engineering solutions are not feasible to provide protection of the geothermal power plant against the formation of new vents.

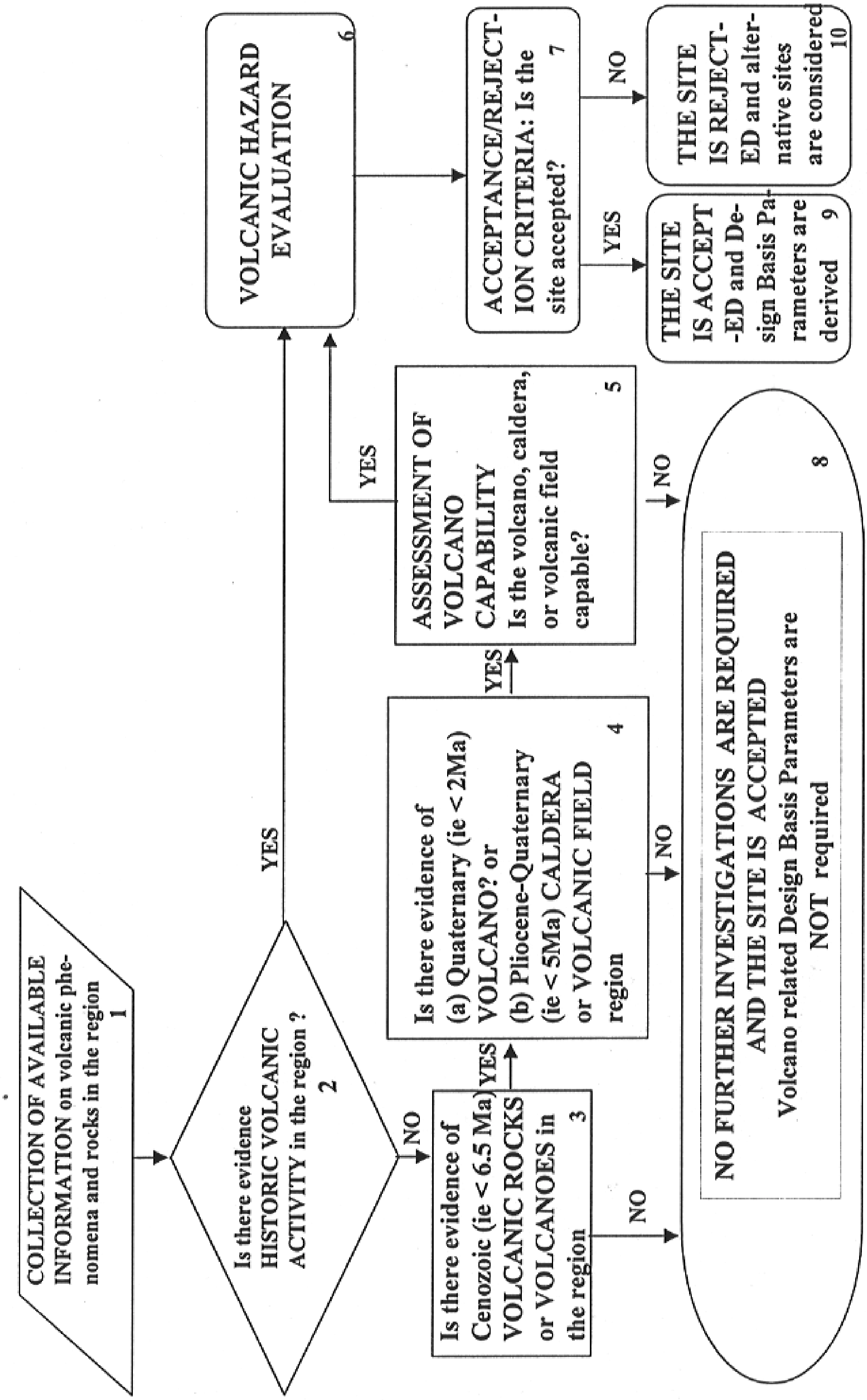

Figure-1
Flow Chart Showing The Process to Satisfy The General Requirement

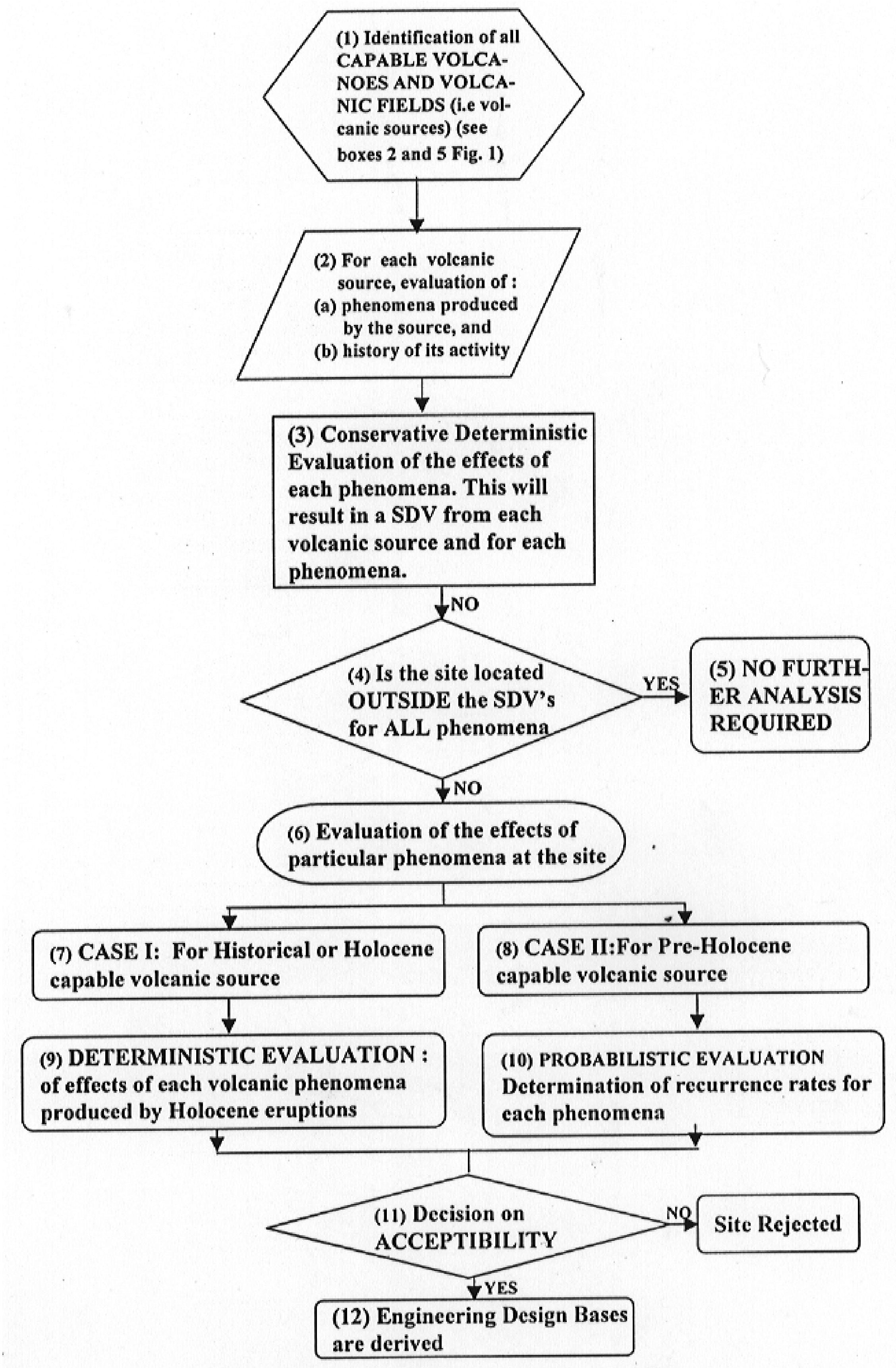

Figure-2
Flow Chart for Volcanic Hazard Evaluation