Basic overview towards the assessment of landslide and subsidence risks along a geothermal pipeline network

Astisiasari[1], Cees Van Westen[1] , Victor Jetten[1], Freek van der Meer[1], Dyah Rahmawati Hizbaron[2]

[1]Faculty of Geo-Information Science and Earth Observation, University of Twente, Enschede, the Netherlands

[2]Faculty of Geography and Environmental Science, University of Gadjah Mada (UGM), Yogyakarta, Indonesia

a.astisiasari@utwente.nl

Abstract. An operating geothermal power plant consists of installation units that work systematically in a network. The pipeline network connects various engineering structures, e.g. well pads, separator, scrubber, and power station, in the process of transferring geothermal fluids to generate electricity. Besides, a pipeline infrastructure also delivers the brine back to earth, through the injection well-pads. Despite of its important functions, a geothermal pipeline may bear a threat to its vicinity through a pipeline failure. The pipeline can be impacted by perilous events like landslides, earthquakes, and subsidence. The pipeline failure itself may relate to physical deterioration over time, e.g. due to corrosion and fatigue. The geothermal reservoirs are usually located in mountainous areas that are associated with steep slopes, complex geology, and weathered soil. Geothermal areas record a noteworthy number of disasters, especially due to landslide and subsidence. Therefore, a proper multi-risk assessment along the geothermal pipeline is required, particularly for these two types of hazard. This is also to mention that the impact on human fatality and injury is not presently discussed here. This paper aims to give a basic overview on the existing approaches for the assessment of multi-risk assessment along geothermal pipelines. It delivers basic principles on the analysis of risks and its contributing variables, in order to model the loss consequences. By considering the loss consequences, as well as the alternatives for mitigation measures, the environmental safety in geothermal working area could be enforced.

Keywords: landslide, subsidence, geothermal, pipelines, disaster, risk, assessment

1. Introduction

Geothermal energy has long been known as a renewable energy resource with the environmental friendly benefits. However, exploiting geothermal energy could also bring a considerable consequence to the environment without implementing a proper risk management plan. Some environmental challenges that are common are: pollution (thermal, noise), wildlife disturbance, and geological hazards (seismic, landslide, subsidence) (DiPippo, 2012a). Moreover, some geothermal fields show a noteworthy number of disasters, especially landslides and subsidence that may bring disastrous consequences (see Table 1).

In a geothermal working area, the pipeline transfers geothermal fluids (steam, liquid, or mixture) from well-pads to the power plant, in the process of generating electricity. However, this essential function may pose a threat to its vicinity, manifested in a pipeline failure. Or else, the infrastructure may be impacted from disasters that may cause pipeline collateral damage. As a primary hazard, pipelines may deteriorate over time and cause failure, manifested in leakage, fracture, burst, etc. While as a secondary hazard, the disaster-induced threat (e.g. landslides, earthquakes, flash-floods, and subsidence) could also generate a pipeline failure.

As a prime infrastructure, geothermal pipelines therefore require an assessment of multi-risk that specifically addresses the risk analysis and its contributing variables, to model the consequences. This multi-risk assessment conveys the possible impact that presents not only the probability of spatial-temporal occurrences, but also the consequence to monetary loss. Besides, risk assessment also encompasses the alternative decisions or strategies for handling the risks.

The importance of multi-risk assessment is within the scope of risk management framework, as proposed by UNISDR (2009); that is to purposively consider the perceived risk, and therefore could enforce the environmental safety. It provides risk information that would be required for selecting mitigation measures, e.g.: site development planning (pipe route, structure construction), operational measures (monitoring, preparedness, insurance, safety standard, regulation), and structural mitigation (slope reinforcement, drainage) (DNV & Muhlbauer, 2012; ENV-1, C-CORE, D.G. Honegger Consulting, & SSD, 2009).

Table 1. Landslide and Subsidence Incidents in Geothermal Working Areas

Landslide	Subsidence
Kamchatka, Russia June, 2007 16.3 million m^3 volume (Gvozdeva, Frolova, & Zerkal, 2015)	Wairakei, New Zealand (1956 – 1971) Subsidence rate: 10 m/yr over 30 km^2 area (Bromley, Currie, Jolly, & Mannington, 2015)
Sungai Penuh – Province of Jambi (January, 2013) Exploration drilling site 4 died, 5 injured, 1 missing http://www.thejakartapost.com/news/2013/01/28/west-sumatra-landslide-leaves-7-dead.html	California, US (1991 – 1994) Subsidence rate: 16 – 18 mm/yr, (Massonet, Holzer, & Vadon, 1997)
Leyte, Philippines (March 1st, 2013) Landslide and sulfuric fumes 5 dead, 9 missing, 31 injured http://www.rappler.com/nation/22868-5-dead-in-lopez-s-leyte-power-plant-incident	Salak – Province of Jawa Barat (1994 – 2008) 16 cm subsidence in 15 yrs (Nordquist, Acuña, & Stimac, 2010)
Wayang Windu – Province of Jawa Barat (May, 2015) 4 died, 14 buried, 55 evacuated http://jurnaljakarta.com/berita-4460-pipa-geothermal-di-pangalengan-meledak-akibat-tanah-longsor.html	Wayang Windu – Province of Jawa Barat (1995 – 2012) 8 cm subsidence in 17 yrs (Masri, Barton, Hartley, & Ramadhan, 2015)
Hululais – Province of Bengkulu (April 2016) Exploration drilling site 1 died, 4 buried, 4 injured http://en.tempo.co/read/news/2016/04/28/307766683/Landslide-in-Bengkulu-Geothermal-Site-Kills-1-Buries-4	Kamojang – Province of Jawa Barat (2006 – 2007) Subsidence at 6cm (Zaenudin, Kadir, Santoso, Abdassah, & Kamah, 2010)

2. Components of the Disaster Risk Assessment

The risk-related terminology is described by UNISDR (2009). Disaster is the adverse disruption to the set of elements (physical, social, and environmental), once exposed by the hazard occurrence. While risk quantifies the probability of adverse consequences due to the exposure to hazardous events. UNISDR describes disaster risk analysis as a method to estimate the probability and consequence of risk, by analysing the component variables of hazard, vulnerability, and coping capacity. Moreover, risk assessment also evaluates the alternative decisions or strategies, related to the estimated risks (UNISDR, 2009; van Westen et al., 2011).

In multi-risk assessment, the loss consequence of several hazard types are estimated through scenarios of probable occurrences from each single hazard over periods of time. To this account, the risk could be presented into three basic aspects, that are (See Figure 1) (Dezfuli et al., 2011; DNV & Muhlbauer, 2012):

- Scenario → a set of adverse situations (damage, failure, destruction, fatality, injury, pollution), resulting in the exposure of assets. These scenarios are used to quantify the consequences for different events.
- Likelihood → the probability appraisal on how likely each scenario may occur. It expresses the frequency in terms of probability or returning period, using historical occurrence data
- Consequence → the quantified impact from each scenario that is implied in loss. The cost of the loss could be monetarized into direct and indirect cost (Doro-on, 2014; Muhlbauer, 2004):
  - Direct cost, e.g.: damages to property, fatality and injury, environmental remediation, profit loss, repair cost, market share disruption, fine and penalty
  - Indirect cost, e.g.: customer discontent, litigation ramification, political reaction, downstream business disruption (agriculture production)

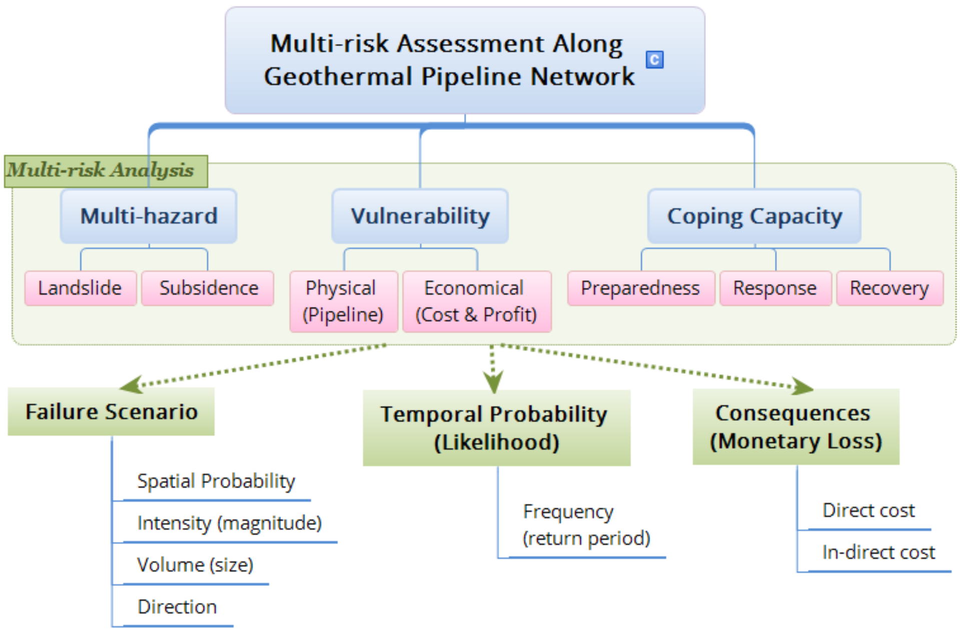

Figure 1. Components of Disaster Risk Assessment

To depict the monetary value of risk, risk curve is used to plot the probability of the scenario against its estimated loss. Figure 2 illustrates the loss values that are represented by y-axis as the consequence value (monetary loss), and x-axis as the temporal-occurrence probability. The area under the curve presents the estimated loss value of total risk (van Westen et al., 2011).

Disaster reduction measures are needed to minimize and reduce the monetary loss. To evaluate the effectiveness of mitigation measures, Cost-Benefit Analysis (CBA) is applied. CBA conveys the beneficial appraisal of financial investment on risk reduction measures, e.g.: structural mitigation, monitoring instrument, and warning system. These risk reduction measures could also apply as a variable of coping capacity.

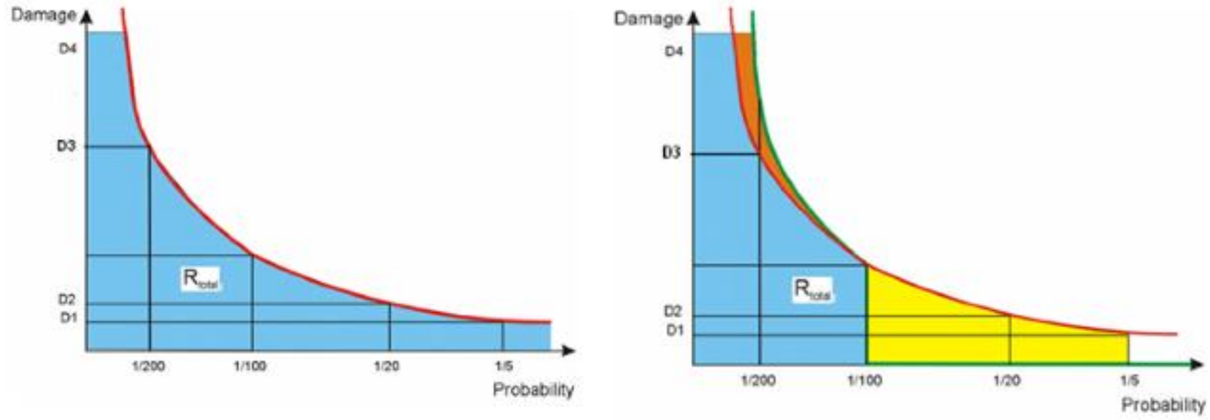

Figure 2. Risk Curve of Monetary Loss (Blue Area), as the Function of Damage Loss over Probability Occurrence: without Risk Mitigation (Left), with Risk Reduction Investment (Right). Source (van Westen et al., 2011)

3. Approaches for the Assessment of Landslide and Subsidence Hazards

3.1. Landslide

Landslide is the phenomenon of soil or rock movement downslope, generated by the force of gravity, which may occur in areas with susceptible slopes, geology, and other precursor events (e.g. earthquake, extreme precipitation) (DiPippo, 2012b; Highland & Bobrowsky, 2008).

Landslide in the geothermal fields occur more frequently due to the presence of hydrothermal alteration zones, and highly weathered materials (Huang & Tian, 2006). This hydrothermal alteration may produce thick soil; and with weathering effects could contribute to slope instability (DiPippo, 2012b).

Many approaches are available to assess landslide susceptibilities in qualitative and quantitative ways, that can be seen from Table 2 (ENV-1 et al., 2009; Jaiswal et al., 2010; Pioquinto & Caranto, 2005; Rex, Devin, & Edwin, 2008):

Table 2. Approaches for Landslide Susceptibility

Methods	Approaches
Qualitative	Geomorphological Analysis • Landscape observation (field or remote sensing technique) • Relatively implicit and rapid • Expert determination
	Variable Weighting & Parameter Scoring • Indexing the contributing factors through criteria matrix • Tools, e.g. SMCE • Expert determination
Quantitative	Statistical Analysis • Parameters comparison for hazard distribution or density, • Univariate or Bivariate (comparing each parameter influence separately), • Multivariate (comparing parameters concurrently. Correlation coefficient and degree of significance are analysed)
	Geotechnical Modelling (Deterministic / Probabilistic) • E.g. slope stability, hydrological analysis • Scenarios of probable events • Mathematically model the driving force (e.g. saturation level, weathered ground, pore pressure, and aquifer level, rainfall, etc.)

Source (ENV-1 et al., 2009; Jaiswal et al., 2010; Pioquinto & Caranto, 2005; Rex et al., 2008)

3.2. Subsidence

Land subsidence is the deformation phenomenon of surface sinking, that may happen due to natural causes (e.g. subsurface erosion, magma process) or by human activity (mining, groundwater or gas extraction) (ENV-1 et al., 2009; Highland & Bobrowsky, 2008; Werner & Friedman, 2010)

Fluid pressure supports the overburden cap soil. Subsidence is likely to happen in the formations with lithostatic fluid pressure, than with hydrostatic fluid pressure. The fluid withdrawal greater than recharge can decrease the pressure. Subsidence can take place in poorly compacted soils like thermal clays; and less frequent in competent formations (where permeability of fracture dominates) (DiPippo, 2012b).

Some approaches to assess subsidence susceptibility are by field reconnaissance of ground displacement, e.g. through:

- Feature and geological observation (sinkhole, fault, wells, submergence),
- Ground-based levelling (geodetic measurement),
- Geophysical or geotechnical analysis for gravity measurement;
- Remote sensing technique by radar or Lidar interpretation

4. Geothermal Pipeline Impact Analysis (Pipeline Failure Probability)

Pipelines may experience disruption or failure due to extreme stress or impact, e.g. mass movement or subsidence. Subsequently, the pipeline failure may also cause environmental consequences due to hazardous material release that may contain flammable, toxic, corrosive, or carcinogenic substances (see Figure 3).

This pipeline damage or failure can be categorized as: leakage, spill, release, crack, breakage, fracture, blockage, rupture, collapse, or burst. Based on the analysis of historical failures, there are four types of pipeline failure mechanisms, that are caused by: (1) third party or external force, like ground movement; (2) corrosivity from material product, atmosphere, and subsurface; (3) pipeline structural design, related to construction, fatigue, integrity; (4) incorrect operation or human error (Doro-on, 2014; EGIG, 2015; Muhlbauer, 2004)

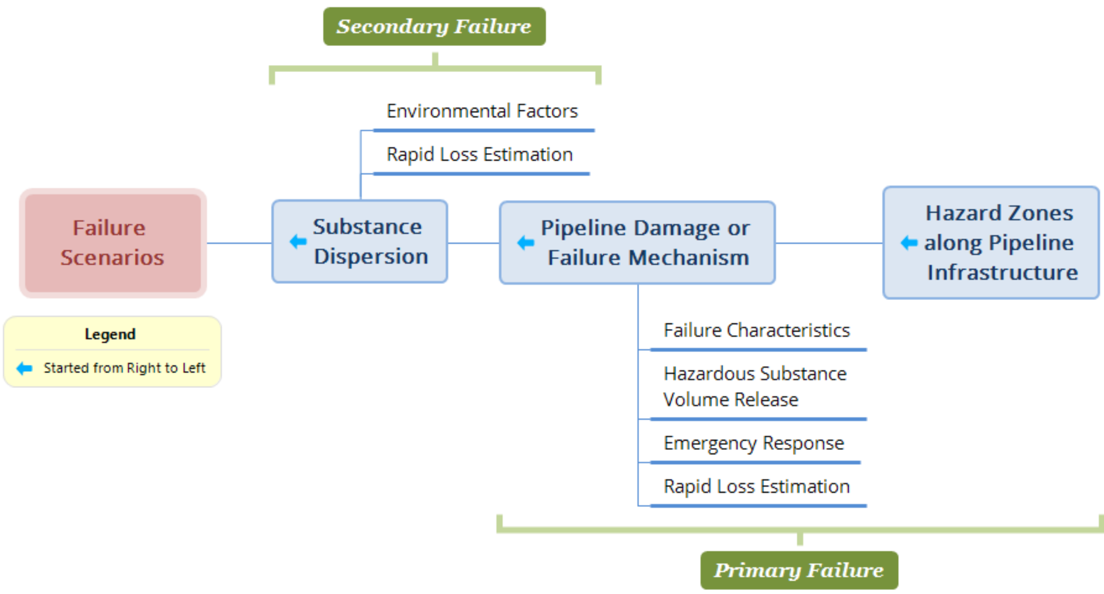

Figure 3. Event Tree for Disaster Induced Pipeline Failure

Therefore, to develop the scenarios for pipeline failure due to the disaster impact, one needs to take into consideration the variables of: (1) pipeline physical characteristic, that is for the resistance and survivability of pipeline from the exposure event; (2) exposure, as in the severity and frequency of events over times; (3) mitigation, that is for the effectiveness percentage of defence measure (DNV & Muhlbauer, 2012; ENV-1 et al., 2009).

4.1. Primary Failure

The physical pipeline characteristics can be used as a base for the analysis of element at risk. Pipeline engineering principle on its structural design is associated with the pipeline strength, toughness, safety, integrity, and value; in response to the abnormal stress from disaster exposure. Therefore, pipeline physical characteristics can account as a basic consideration for failure event scenarios. Table 3 shows the main physical characteristics of pipeline and its parameters (Liqiong Chen et al., 2014; DNV, 2010; EGIG, 2015; ENV-1 et al., 2009; Miranda & Lopéz, 2011; Muhlbauer, 2004).

Table 3. Physical Characteristics of Pipeline for the Element at Risk Analysis

Physical Characteristic	Parameters
Construction Design	• Material and coating specifications; • Pipe support: surface, buried, hung, elevated, berm, culvert, etc; • Pipe-bends or flexibility: umbilical, curving angle; • Seamless, joints, submerged, electric resistance; • Utility or component support: valves, fittings, anchor, tank, vessel, pump • Design code for safety standard and tolerance
Dimension size	• Diameter; • Wall thickness; • Length
Load content	• Temperatures & Pressure; • Product type (gas, liquid, combination); • Flow rate and volume (flow rate by time) • Density and viscosity • Solubility • Hazardous type (ignitability, reactivity, toxicity, corrosivity, carcinogenicity)
Route and layout	• Location of separators, power plant, pipes; • Slope, elevation, land-cover, landowner, soil type
Construction, Support load, and Technical structure	• Construction Year • Joints or connectors, swan neck, • Expansion loops, anchors, stopper, elbow section, valves; • Weight support, shock absorber; • Ground allowance level: stress & seismic, leakage & break; • Corrosion allowance level • Minimum yield strength (MPa)

There is always a certain level of uncertainty on how pipelines behave or respond, once subjected to extreme conditions or abnormal stress. To this account, interaction between soil and pipelines is considered in the soil spring stiffness analysis. It presents soil loads direction acts towards the pipeline resistance (ENV-1 et al., 2009). Therefore, besides the pipeline physical characteristic, soil properties should also be analysed. This geotechnical analysis should model soil spring stiffness through soil variables i.e.: friction, cohesion, saturation, and permeability.

4.2. Secondary Failure

The dispersion of hazardous material release may contaminate the environment. The spatial impact to the environment may differ, based on: (1) failure characteristics (type, size, volume released); (2) environmental conditions (weather, morphology, geology, soil); (3) preparedness and response (detection and warning system).

Generally, the environmental effects from pipeline failure can be characterized from several proxies, e.g.: infiltration, drainage, groundwater, weather, landcover, and slope. These can be used to determine hazard zones that are in approximate distance from the possible occurrence of pipeline failure.

Hazard zones along the pipeline network may have different characteristics in terms of pipeline structure and environmental characteristics. Therefore, grouping the pipeline into segments is a practical way to assess the risk. Basically, the segmentation could be done by: (1) fixed-length, or (2) dynamic segmentation on certain criteria or parameters. The hazard susceptibility analysis can then identify the hazard density for each pipeline segments (See Figure 4).

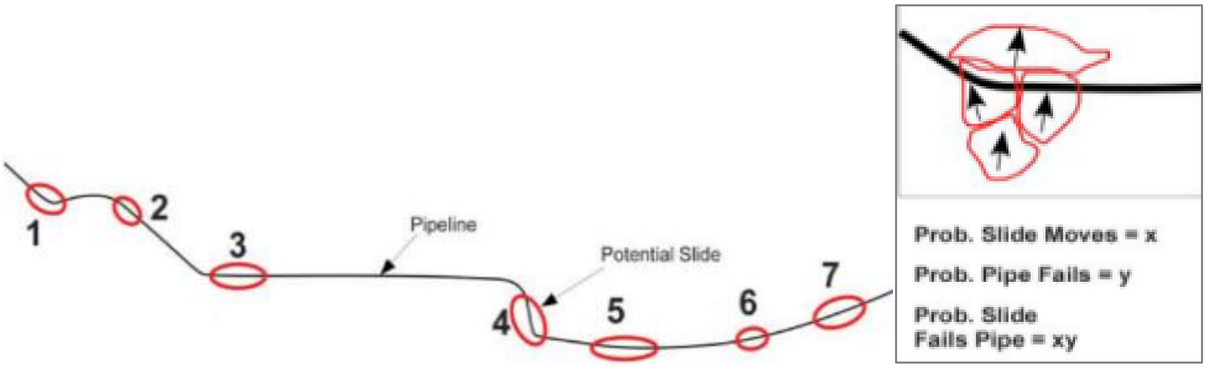

Figure 4. Pipeline Dynamic Segmentation Based on Hazard Susceptibility Zone
Source (ENV-1 et al., 2009)

4.3. Likelihood (Temporal Probability) of Pipeline Failure

After the susceptible areas are identified, pipeline failure frequency is analysed. It is the temporal probability appraisal on how each failure scenario is likely to occur. The likelihood requires a set of parameters of historical occurrence data to be associated with pipeline physical characteristics and mitigation measures. The linkage correlations between these likelihood parameters are analysed statistically (See Figure 5) (ENV-1 et al., 2009)

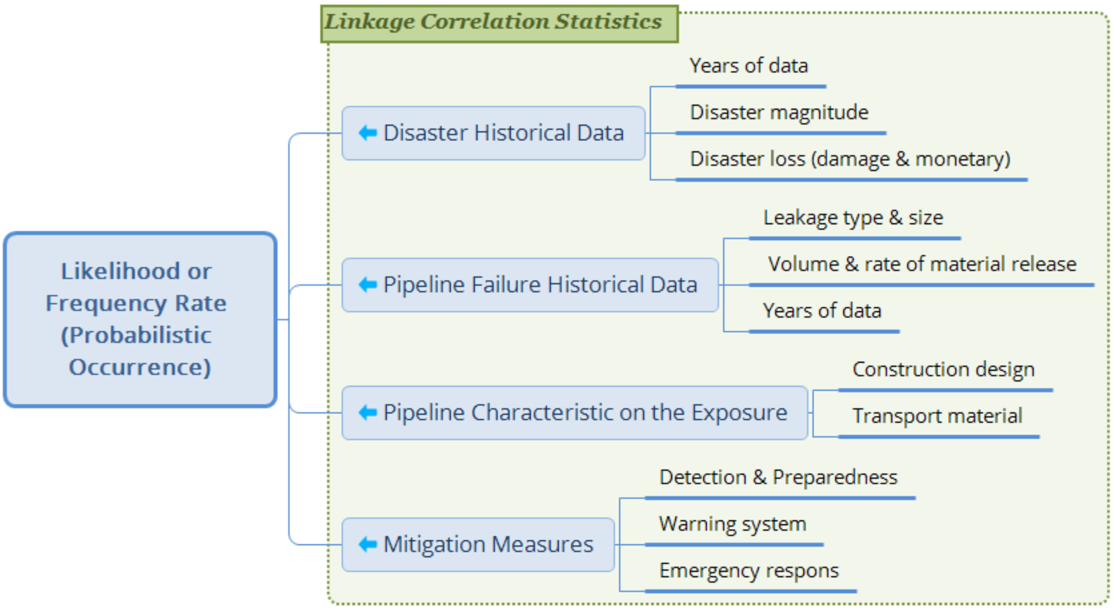

Figure 5. Determining the Likelihood for the Probable Occurrence Scenario through Parameters

5. An Approach for the Assessment of Landslide and Subsidence Risks Along the Geothermal Pipeline

The basic overview of an approach towards the multi-risk assessment along the geothermal pipelines could be seen through the general conceptual framework from Figure 1. It basically combines the predictive risk scenarios from different types of disaster (See Figure 6) (van Westen et al., 2010; W. Marzocchi et al., 2009):

A. Data preparation for each variable (hazards, vulnerabilities and elements at risk, coping capacity).
B. Hazard assessment to identify the predictive scenario of:
    a. Susceptible hazards location
    b. Temporal probability, return period (frequency of failure occurrence),
    c. Hazard characteristics: magnitude and intensity, volume (size), change and direction
C. Vulnerability assessment of pipeline element at risk
    a. Pipeline physical characteristics
    b. Pipeline economical value
    c. Pipeline failure characteristics: hazardous substance release, failure type and size
D. Coping capacity, as measures for the disaster risk reduction (preparedness, response, and recovery)
E. Risk assessment, by integrating variables spatially to assess the probabilistic consequence at respective return periods (See Figure 6)
    a. Loss scenario (monetary value) to pipeline and possibly to environment
    b. Acceptance level of acceptable risk

6. Discussion

The assessment of multi-risk along the geothermal pipelines is still not sufficiently studied and understood. There is a need to develop new methods to address the disaster risk assessment in geothermal fields; that is taking into account the hazard, vulnerability, and capacity analysis for enforcing the environmental safety. Therefore, it is important to find the best practical method to model the probable scenarios in terms of spatial-temporal probability of pipeline failure and possible monetary loss.

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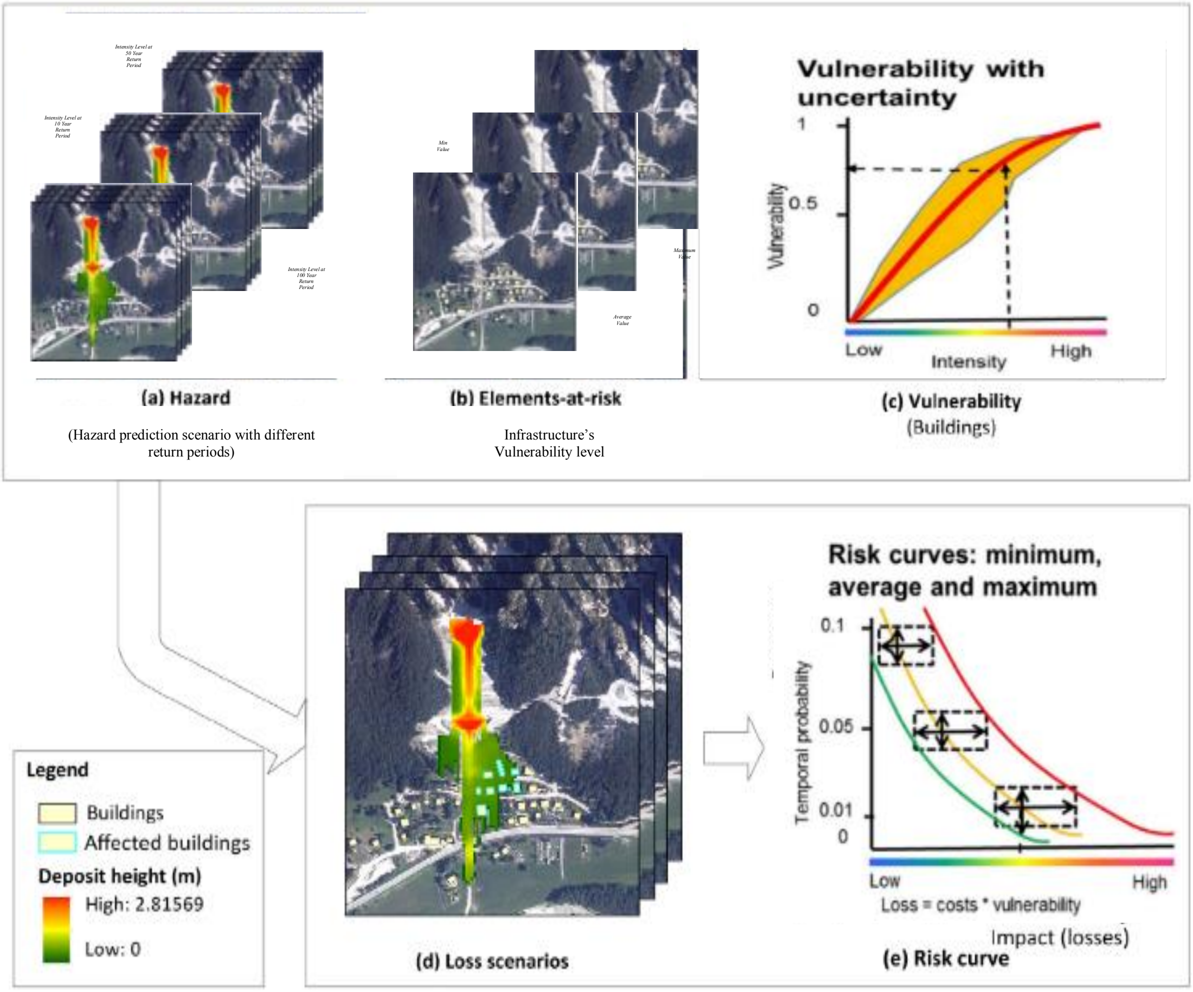

Figure 6. Approach for the Assessment of Multi-risk, Presented as scenario and its loss value by Respective Returning Periods. Source (Aye et al., 2016; Chen et al., 2016)

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