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Important Parameters Related With Fault for Site Investigation of HLW Geological Disposal

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Large earthquakes with ($M_W > \sim 6$) result in ground shaking, surface ruptures, and permanent deformation with displacement. The earthquakes would damage important facilities and infrastructure such as large industrial establishments, nuclear power plants, and waste disposal sites. In particular, earthquake ruptures associated with large earthquakes can affect geological and engineered barriers such as deep geological repositories that are used for storing hazardous radioactive wastes. Earthquake-driven faults and surface ruptures exhibit various fault zone structural characteristics such as direction of earthquake propagation and rupture and asymmetric displacement patterns. Therefore, estimating the respect distances and hazardous areas has been challenging. We propose that considering multiple parameters, such as fault types, distribution, scale, activity, linkage patterns, damage zones, and respect distances, enable accurate identification of the sites for deep geological repositories and important facilities. This information would enable earthquake hazard assessment and lower earthquake-resulted hazards in potential earthquake-prone areas.

Keywords: Fault damage zone, Active fault, Surface rupture, Respect distance, Deep geological disposal

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1. Introduction

In South Korea, the nuclear power plant industry has grown steadily since 1978, the first construction of commercial nuclear power plant, Kori #1. As many nuclear power plants have continuously been operated, the amount of spent fuel has also been accumulated. However, the space in the interim storage pools for spent fuels of each nuclear power plant will almost be saturated by 2024 [1]. Therefore, the spent fuel management has emerged as a very critical issue in the nuclear industry not even in Korea but also all over the world [2-4].

The scientific communities of most countries with nuclear power plants have generally accepted deep geological disposal as one of the best solutions to solve the problem [5-6]. However, except a few countries such as Finland and Sweden, most of the countries face many challenges in siting decision such as scientific, political and public acceptability [7]. To select a suitable site for deep geological disposal, it has been adopted a systematic process for narrowing down from large areas to specific sites for characterization and identification of the geologies and geological structures [8]. They proposed four stages for the siting process for deep geological disposal of radioactive wastes as follows; 1) conceptual and planning stage, 2) area survey stage, 3) site characterization stage, 4) site confirmation stage. Moreover, it is not appropriate to depend on real-time monitoring, remedial actions, and other active institutional controls to ensure the long-term safety of deep geological disposal because of the related extensive time span for disposal [8]. Thus, the safety of a deep geological disposal strongly depends on both geological and engineered barriers to afford proper protection from radiation by gradual processes of predicted and probable events or accidents which may affect the deep geological disposal. Some considered factors can strongly influence on the site selection of potential sites for deep geological disposal. These factors can be developed based on long-term safety, technical feasibility and socioeconomic, political and environmental considerations [8].

In South Korea, the investigation process for siting of deep geological disposal was proposed as three stages [9-10]. The first literature research stage in nationwide scale is mainly conducted based on review on published data and information. Several candidate areas are selected through the procedure of first stage. The second investigation stage on candidate areas is extracted from first stage, which is focused on regional geological characteristics, conducting surface geological survey and drilling for evaluation of the geological characteristics in depth. The third detailed investigation stage is conducted for final candidate sites.

Choi et al. [10] suggested a matrix system of the geological elements to be investigated for each stage of site investigations, which are classified into aspect, item, and parameter on the site investigation method for deep geological disposal. They also proposed 7 aspects for geological elements such as lithology, structural geology, seismology, Quaternary geology, hydrogeology, geochemistry, and engineering geology, where each aspect is composed of more items and parameters in detail. Kim et al. [11] also suggested the 17 items and 103 parameters with brief explanations for the assessment factors of HLW. Aspect of structural geology is composed of brittle structures, ductile structures, and neotectonics containing 8 investigation parameters such as large fault zone, active fault, volcano, ductile shear zone, fold, foliation, persistence and segment, and respect distance [10]. However, because the proposed investigation items and parameters on each stage are rather comprehensive, specific items for fault evaluation should be required to secure the safety of the deep geological disposal.

In general, the long-accumulated stress is abruptly released through earthquake along active fault during short time. Moderate to strong earthquakes (i.e. $M_W > \sim 6$) can generate not only strong ground motion but also permanent displacement or deformation including surface ruptures [12-14]. Although surface ruptures are concentrated along a relatively narrow fault zone, it may cause tremendous damage to most types of structures [e.g. 15-16]. Actually, fault related structures such as fault damage zones, asymmetric patterns of surface rupture and linkage between faults can affect the respect distance of fault, which are very complicated depending on the fault type, slip sense, evolution stage, and location around the fault [17-18]. Moreover, it is important to properly assess the potential hazard of the faults characterized the permanent deformation zone producing serious damage around important sites or facilities such as nuclear industries and huge industrial facilities [17-18]. Thus, it is necessary to estimate the respect distance from the fault. Therefore, we will suggest the substantial parameters to be considered for assessment of fault in each investigation stage for proper deep geological disposal sites to reduce earthquake hazards, such as distribution of fault, fault scale and linkage, fault types and damage zones, fault activity, and respect distance, etc.

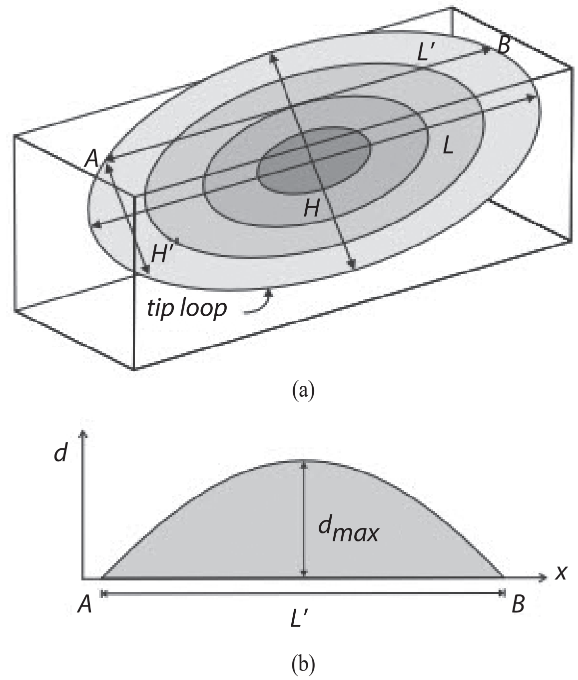

Fig. 1. (a) Diagram to descriptive displacement distribution on an elliptical fault surface of length (L) and height (H). Note that shading density indicate the increasing displacement towards center of fault. A–B line is the fault intersect the upper surface of the block. (b) Displacement (d)-distance (x) plot of fault trace along line A–B [22].

2. Important Parameters for Fault Evaluation

2.1 Spatial Distribution of Fault

Brittle deformation in the upper crust is mainly associated with opening and slip on fractures, generating faults, veins and joints. These occur throughout a wide range of scales from mm or cm scale veins and joints to large fault zones with km scale displacements [19]. In general, fault zone is comprised of fault core, damage zones, and wall rock. Most of the displacement is concentrated in fault core, and damage zone is closely related to the growth or evolution of fault zone [e.g. 20-21]. Based on the accurate information of the locations of faults or active faults and deformation patterns, earthquake prone areas could be avoided during the process of each stage of site investigation. Therefore, it is necessary to investigate the spatial distribution of faults within the target area with an appropriated scale for each stage. For example, in the nationwide investigation stage, it should be conducted based on published small-scale geological maps to identify fault locations. Then, as the investigation stages from regional (area) to a local (site) areas, the accurate location of faults should be identified using a detailed spatial distribution map of faults. Moreover, it is necessary to identify the distribution or locations of faults through not only published fault maps but also conducting detailed fault investigation such as surface geological surveys and drilling surveys for deep environments.

2.2 Fault Scale and Linkage

Fault size is specified by its total surface area in 3-D, however, to present fault shape in 2-D, measures of fault length are generally used [22]. Fault length is commonly defined in one of two ways. First, fault length is measured in a direction parallel to the slip vector [e.g. 23-24]. Second, fault length is considered as trace length in map view or the

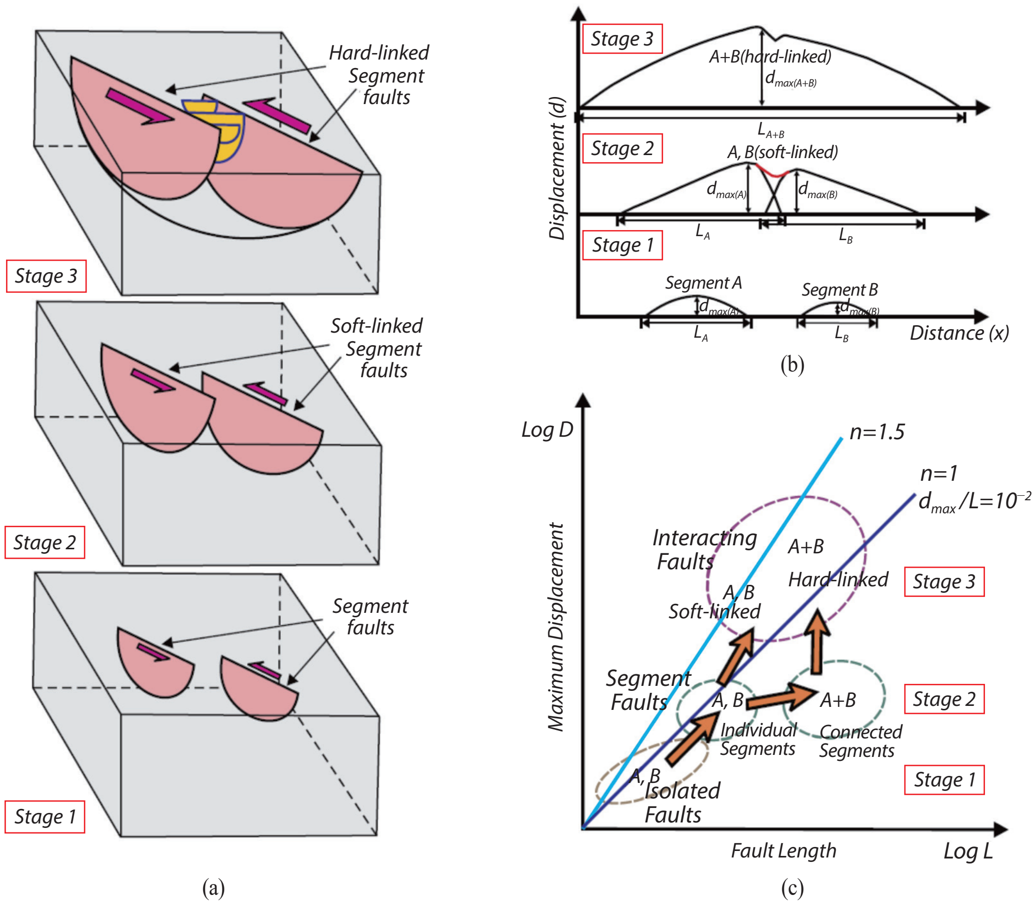

Fig. 2. Block diagrams, displacement profiles, and maximum displacement (d_{max}) / fault length (L) plots for fault segmentation and linkage [22]. Faults evolve from isolated faults to interacting faults throughout segment linkage. The ratio of d_{max} / L increases, showing a step-like path. The fault lengths abruptly jump at the stage of segment linkage.

longest horizontal dimension [e.g. 25-28].

Kim and Sanderson [22] proposed that fault length (L) is the longest horizontal or sub-horizontal dimension long a fault plane, and fault trace length (L') is the exposed fault length on an arbitrary horizontal or sub-horizontal plane (Fig. 1). The relationship among fault length, maximum displacement, and moment magnitude has been intensively studied in the past [e.g. 22, 29]. Therefore, it is important to trace and evaluate the fault length, particularly around important sites such as nuclear power plants and deep geological disposal sites, etc. Thus, fault length should be carefully investigated and evaluated on each investigation stage.

Fault length, total displacement, and fault activity has been estimated based on the width of brittle fault zone because it can indicate the fault scale and history [e.g. 30-32]. The complexity of a fault zone generally relies on the fault activity and various conditions such as stress, pressure, strain rate, temperature and lithology, which can vary temporally and spatially [33-36]. Thus, the width of fault zone is variable along a fault. Furthermore, some measurement methods have many limitations, which leads to systematic under- or overestimation of the maximum fault length and the maximum displacement can be difficult to measure along the whole fault trace.

The displacement around the fault linkage zones extremely varies and abruptly changes at different locations

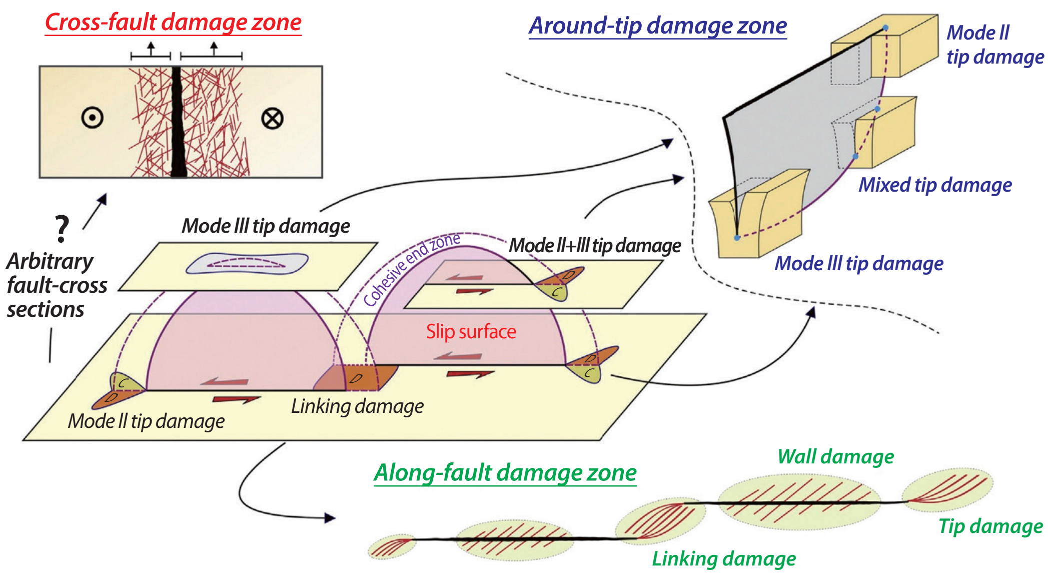

Fig. 3. Schematic diagram of fault damage zones around a left-lateral strike-slip fault [50]. Fault damage zones can be consisting of along-fault, around-tip, and cross-fault damage zones based on exposures, concerns, and descriptive concepts.

and in different evolution stages of segment linkages [e.g. 22]. Peacock and Sanderson [37] suggested three stages in segment linkage growth: *isolated faults* (stage 1), *soft-linked faults* (stage 2), and *hard-linked faults* (stage 3). The displacement is almost zero in the linkage zone when two isolated faults begin to interact. However, hard linked fault rapidly accumulated displacement around the linkage zone and abruptly increased the fault length because it acts as a single fault [Fig. 2; 22].

To understand fault scale and linkage, several detailed investigations should be carried out from the nationwide scale to the final candidate site scale such as aerial geophysical explorations, surface geophysical and geological surveys, etc. Moreover, drilling surveys such as borehole geophysics, single-hole loggings, cross-hole geophysics, and hole-to-surface investigations are also required to recognize the deep characteristics of fault, it can offer useful information of fault geometries in depth.

2.3 Fault Types and Damage Zones

Fault damage zones refer to the volume of deformed wall rocks around a fault surface resulting from the ignition, propagation, interaction, and build-up of slip along the fault [30, 38-40]. It can provide useful data on fault propagation and growth [38, 41-42], earthquake initiation and termination [43-47], and fluid flow [48-49]. Kim et al. [39-40] systematically described and classified various fault damage patterns, which is locally concentrated damage structures along a fault system. They suggested that the variety of fault damage patterns as a result of 1) exposed locations around a fault, 2) different stages in the evolution of a fault system, and 3) different tip modes of a propagating fault. It is remarkable that clusters of deformed structures can create variations in the width of fault damage zone. Choi et al. [50] also classified fault damage zones into three categories: along-fault, around-tip, and cross-fault damage zones, concentrating on the observations and concerns of fault exposures (Fig. 3). The along-fault damage zone is applied to describe the various damage structure along fault traces, which is considered the position along a fault zone. The around-tip damage zone, a 3-D descriptive concept, is used to express the different kinematics and geometries of previous tip damage zones relying on the slip sense and tip

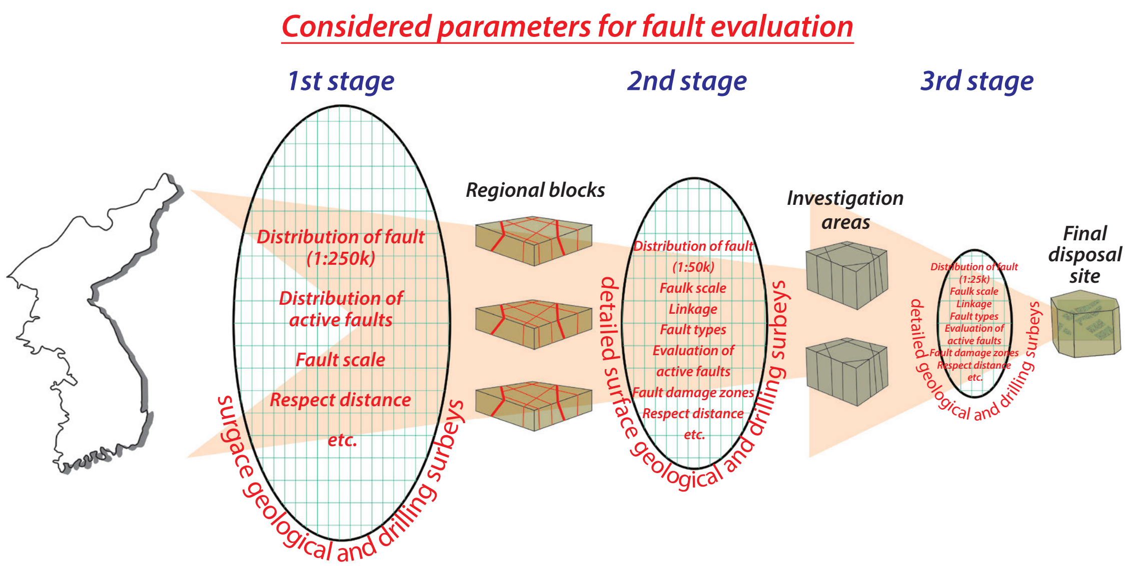

Fig. 4. Schematic diagram of important parameters related fault for site investigation of HLW geological disposal. Note that several substantial parameters for assessment of fault should be considered to recognize the proper sites for deep geological disposal sites as well as safe regions for important facilities.

mode [50]. The fault traces are parallel to strike-slip sense or perpendicular to dip-slip sense to the main movement sense, and tip damage zones are divided into mode II and mode III [50]. The cross-fault damage zones are generally used to large or mature fault zones and these can be classified into extremely deformed zones, mixed zones, and transition zones [51-54].

The major surface ruptures were concentrated at main fault plane showing simple linear pattern, whereas the minor surface ruptures along the major surface ruptures were developed in the tip- and linkage damage zones developing complex patterns. For example, strike-slip components were abruptly transferred to dip-slip components in tip and step-over zones at natural strike-slip fault indicating the slip compensation [55]. It strongly indicates that strain, slip distribution and surface rupture patterns are mainly controlled by the fault damage zones.

The rock volume around the surface ruptures experiences stress changes that strongly related to the displacement, aftershocks, damage zone associated with earthquake along a fault [47]. Moreover, several studies have indicated the relationship between the main shock locations, aftershocks, and secondary fractures or damage zones along a strike-slip fault [e.g. 47, 56-57]. The main shocks are not located in the largest slip or center of the rupture, but occurred at the one end of the surface rupture with relatively lower slip [58-59]. The main shock propagates accumulating slip with a strong directivity from the rupture initiation point and the increased slip abruptly decreases generating damage structures until terminated (see the fig. 4 in [18]). In addition, a cluster of aftershocks is mainly occurred in damage zones, because it is associated with secondary fractures accommodating the main slip (see the fig. 2 [47]). It strongly indicates that the distribution and location of aftershocks and the main shock are depending on the rupture propagation, slip, and damage zone [47].

Asymmetric pattern of fault damage zones is very common in naturally developed fault in both across- and along faults [e.g. 39, 47, 54]. The asymmetric widths of damage zone are dependent on different stress conditions in footwall and hanging wall of dip-slip faults [35, 60] as well as different rock properties across the fault [54, 61]. In general, damage zone is wider near hanging wall than near footwall [16, 20, 54]. In along fault, damage zones are more dominant in dilational quadrants rather than in contractional quadrants, particularly in tip and linking damage zones. Brittle rocks are broken more easily under tension rather than compression under a shallow crust. Hence, to properly estimate the widths of deformation zone, it is necessary to understand 3-D architectures and related asymmetric patterns of fault damage zones.

2.4 Fault Activity

The most considerable concern on earthquake researches is predicting future devastating earthquakes to facilitate in earthquake hazard assessment. Many large earthquakes are generated by reactivation of pre-existing active faults, and it is a crucial work both to identify the active fault and to decipher its past earthquake activities. Because active fault and related fractures associated with large earthquakes can significantly disrupt the part of the engineered and geological barriers as well as damages to the spent fuel containers. The paleo-earthquake records are actually large earthquake records ($M_W > 6.5$) or great because geological records by small and moderate size earthquakes are rarely produced or preserved near the surface [62]. Geological records, containing various information of large paleo-earthquakes can provide very significant information on paleo-earthquakes in tectonically quiet regions where large earthquakes do not often occur.

Primary effects (surface ruptures) and secondary effects (tsunamis, hydrogeological anomalies, ground cracks, slope movements, trees shaking, liquefactions, dust clouds, and jumping stones) are generated associated with large earthquakes [63]. In particular, surface ruptures and related parameters are directly connected to the released earthquake energy from the seismogenic source. Thus, the scale of earthquake is typically expressed in both surface rupture length and maximum displacement. Consequently, these parameters can be used to estimate the moment magnitude of earthquake based on the empirical relationship between surface rupture length (or maximum slip) and moment magnitude [29]. Therefore, it is very important to identify the distribution of active faults and determine the related earthquake parameters to evaluate potential earthquakes where important or dangerous facilities are located.

Several fundamental techniques for active fault investigation have been used to get paleoseismological data. To identify the geomorphic deformation features, some remote sensing technics and data (DEMs, satellite images, aerial photographs, radar images, etc.) have been generally used in regional scales. In local scales, detailed geomorphic analyses based on the deformation of Quaternary topography should be carried out, because surface deformation associated with large earthquakes could be so small and removed by later erosion processes. Moreover, several geophysical methods have been used to identify active fault in shallow depth and to set a position of trench and drilling sites. It could be also very useful for tracing active fault to depths greater than reached by excavation of trench and to recognize blind faults.

2.5 Respect Distance

The definition of the deformation zone varies among research groups. For example, Munier et al. [64] suggested a new term, respect distances, to avoid ambiguity of the definition of the deformation zone for disposal site selection. Because the concept of respect distance is very important to assess earthquake hazard around faults, the complexity of faults or surface ruptures should be considered around the deep geological disposal site.

The width of fault zone has been used as a parameter in assessing the total displacement, length, and activity of the fault, because it could be an indicator for the fault history and scale [30-32]. The relationship between maximum displacement and fault length has been mainly studied to estimate the unknown fault dimension based on empirical fault scaling relationship between fault parameters [22].

However, these relationships are poorly correlated because the data are produced by combining different and individual data sets were on limited fault length scales [22]. In addition, some measurement methods have some limitations leading to the under- or overestimation of the maximum fault length, for example, the displacement could not be measured within the central part of fault trace. Furthermore, the displacements around fault linkage zones varies and abruptly changes depending on different locations and evolution stages of segment linkages [e.g. 22]. Therefore, several controlling factors can affect to both fault length and displacement, thus estimation should be carefully considered based on accurate statistical data.

The width of deformation zones or damage zones is one of the important factors when estimate the affected areas of a site related with important facilities. Defining the boundary between fault damage zones and wall rock is another issue. Although it is commonly based on fracture frequency, it is not easy, because various criteria could be used depending on researchers. However, this limitation could be overcome new concept of the boundary based on background fracture density and cumulative frequency measurement [50]. This suggested method of combining the interval and cumulative frequency of fractures can be a crucial tool for defining damage zone boundaries. The evaluation of damage zone width based on this method could greatly reduce the data scattering in scaling relationship between displacements and damage zone widths.

Asymmetric pattern of fault damage zones is commonly developed in both along- and across-faults in nature [e.g. 39, 47, 54]. In strike-slip faults, fault damage zones are more dominant in dilational quadrants rather than contractional quadrants, particularly in linking and tip-damage zones. Thus, the width of main trace is relatively narrower than those of tip- and linking damage zones in strike-slip fault (see the fig. 6 in [18]). The linking- and tip-damage zones in mature strike-slip fault show more extensive and complex volume of damages rather than those along the walls of simple faults.

For dip-slip faults, however, damages are generally concentrated on the hanging wall rather than footwall because of different stress conditions (i.e., free surface on the hanging wall to release stress) and propagation of seismic waves (i.e., upward propagation through hanging wall; see the fig. 7 in [16]). Therefore, to understand damage characteristics and establish proper respect distances, it is necessary to understand the 3-D architectures and related asymmetric patterns including more intensive investigation on the hanging wall parts of dip-slip faults (see the fig. 9 in [18]).

Finally, it is difficult to standardize all types of fault zone because fault zones are very complicated in nature. Therefore, it is important to estimate proper respect distances perpendicular to surface ruptures based on accurate tracing of active fault and identifying of damage zones. These could enable us to protect deep geological disposals and important facilities from earthquake damages.

3. Discussion

3.1 Proper Definition of Active Fault for Deep Geological Disposal

Because the amounts of damages and causalities rely on earthquake scales, the basic concerns related with an earthquake are location, magnitude, and timing of the earthquakes [18]. The fault activity is defined by the accumulated displacement or stress over a geological time period. The general definition of active fault is *'a fault on which slip have occurred recently and is likely to occur in the future'* [65]. However, there are various definitions about the recent activity [e.g. 66-71]. The time period is various from 10,000 years to the whole Quaternary time. Thus, it is difficult to unify them into one definition for active fault because various definitions could be used, depending on the purposes, regulations, countries and organizations. In general, for high-level radioactive wastes, especially spent fuel, isolation period is recognized to be at least 100,000

Table 1. The considered parameters for fault evaluation on deep geological disposal site

Item	1st stage parameters	2nd stage parameters	3rd stage parameters
Fault	Distribution map (1:250k)	Distribution map (1:50k)	Distribution map (1:25k)
	Length	Length	Length
		Linkage	Linkage
		Fault types (strike-slip/dip-slip)	Fault types (strike-slip/dip-slip)
	Distribution of active faults	Evaluation of active faults	Evaluation of active faults
		Range of fault damage zones	Range of fault damage zones
	Respect distances	Respect distances	Respect distances

to 1,000,000 years [72]. It should be no geological process to secure long-term safety of disposal site, such as faulting and fracturing which can cause catastrophic damage geological and engineering barriers during specific period. Therefore, it is necessary to define proper time period of active fault in terms of deep geological disposal.

3.2 Definition and Application to Lineament

Lineament is generally defined as any simple, mappable, or composite linear feature on earth surface where the regions are aligned in rectilinear or curvilinear structures recognized distinct patterns from adjacent features [73-74]. Three types of lineaments are genetically separated; 1) geological lineaments, 2) geomorphological or topographical lineaments, 3) man-made, or non-geological lineaments [74]. Lineaments are generally used as references to any linear geological features of different scale, age, depth, and origin [73]. Lineaments are mainly associated with faults, linear zones of fracturing, bending deformation, and increased permeability of the sub-surface. Thus, lineament is strongly related with geologic structures such as faults. Therefore, we suggest that lineaments should be considered and investigated as potential faults during site investigation stages for deep geological disposal because lineament is a surface expression of geological structures.

4. Conclusions

Large earthquakes ($M_W > \sim 6$), producing most of the accumulated stress along faults, generally generate surface ruptures as well as strong ground motions. Surface rupture is the most primary effects of large earthquakes, producing permanent deformation with displacement. Although ground motions can be overcome by seismic design or controlling the local geological foundation, surface ruptures is difficult to avoid in the earthquake prone areas, where it can cause tremendous damages to important facilities or infrastructures. Furthermore, we cannot control the earthquake characteristics such as magnitude, seismic wave characteristics, distance from the epicenter, earthquake depth, local geological condition, etc.

Therefore, faults and surface ruptures associated with large earthquakes can severely damage to the geological and engineered barriers as well as the spent fuel containers in the deep geological disposal site. However, if we have information on accurate locations of active faults or potential surface ruptures, we could exclude or avoid the earthquake prone areas during the site investigation stages for deep geological disposal. Therefore, detailed analyses on faults and surface ruptures based on the concepts of fault damage zones and earthquake mechanism can provide a lot of crucial information such as propagation direction of earthquake and surface rupture, damage distribution of main shock and aftershocks, and asymmetric displacement pattern. Moreover, fault damage zones should be thoroughly considered because proper evaluation of respect distances is very important for earthquake hazard analysis for deep geological disposal site. Finally, we suggest the crucial parameters of fault hazard evaluation for proper investigation stages, those should be conservatively applied to evaluate and select proper deep geological disposal sites (Fig. 4; Table 1).

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