Mechanism analysis of hazards caused by the interaction between groundwater and geo-environment

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Abstract Groundwater is as an important geological agent. Moving groundwater may change the geological environment and cause geological hazards. Therefore, the interaction between groundwater and geo-environment has attracted increasing attention of hydrogeologists, geotechnical engineers and environmental geologists. In general, three main types of interaction between groundwater and the geological environment are identified in this paper, with several special processes for each one. These types include physical interaction, with processes of lubrication, softening or weakening and strengthening of bound water, chemical interaction with processes of ion exchange, dissolution, hydration, hydrolysis, corrosion and oxidation-reduction, and mechanical interaction with processes of hydrostatic pressure and hydrodynamic pressure. The interactions between groundwater and the geological environment can affect the deformability and strength of rock or soil masses. The geological process, engineering activity and heat can change the geo-stress field, recharge, throughflow and discharge conditions of groundwater. The consequence of interactions between groundwater flow and geo-stress changes the geological environment. Meanwhile, the interaction processes can induce geological hazards, such as reservoir-induced earthquakes, landslides, flooding of mines, ground engineering hazards, instability of dams, the collapse of cavities in carbonate and evaporate rocks, land subsidence and earthquakes.

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Introduction

In recent years, the frequency of hazards has shown an increasing tendency due to the changes in natural conditions and the increase in the intensity and scale of engineering activities. According to preliminary statistics, geological hazards such as reservoir-induced earthquakes, landslides, flooding of mines, ground engineering hazards, instability of dams, the collapse of cavities in carbonate and evaporate rocks, land subsidence and earthquakes, are mostly related to groundwater movement. Accordingly, the research on the relations between groundwater and geological hazards are of great importance. To reduce and control geological hazards, the analysis of the coupled seepage field and stress–strain field in rock or soil masses is the basis of the quantitative solution of the problem.
In the study of the relations between seepage and stress, Louis (1974) showed a negative exponential relation between the permeability coefficient and stress based on the analysis of pumping test data in a dam site. Snow (1968) proposed a permeability coefficient expression of a set of parallel fractures under the stress action. Oda (1985) derived a unified expression to describe the relation between seepage flow and stress by using a crack geometrical tensor. Bai and Elsworth (1994), Bai and others (1997), and Nagaraj and others (1994) have studied coupled processes of fluid flow and stress based on stress-dependent permeability. Witherspoon and others (1980) have analyzed the validity of cubic law in a deformable rock fracture. Aydin (2001) has reviewed the problem of flow, transport and deformation in fracture media. Wu and Zhang (1995) derived the fractal geometrical relation between the permeability coefficient and stress in terms of experimental data. Wu and Chai (2001) analyzed seepage forces exerted on fracture network of rock mass including hydrostatic pressure and hydrodynamic pressure.
In the analysis of coupled seepage field and stress–strain field, Noorishad (1982, 1989) analyzed the mechanism of coupled seepage and stress in a discontinuous joint rock

mass and determined the finite element method based on the joint elements. Oda (1985, 1986) developed an equivalent continuum model for coupled seepage and stress fields analysis based on permeability tensor and stress tensor methods. Wu (1997) used a generalized double porosity media model for coupled seepage and stress fields analysis in rock masses to analyze the slope stability of hydropower projects. Jing and others (1995), and Stephansson (1995) developed a mathematical model of coupled thermo–hydro–mechanical (THM) processes for safety analysis of radioactive waste repositories. Tsang and Stephansson (1996) presented a conceptual introduction to coupled thermo–hydro–mechanical processes in fractured rocks. Wu and Gao (1997, 1998), taking the temperature field into consideration, developed the continuum model and the double porosity media model for coupled seepage field and stress field analysis in oil–gas migration. Zhang and others (1997) carried out integrated shear and flow parameter measurement. Louis (1969), and Ingebritsen and Sanford (2000) have studied the problems of groundwater flow and geo-environment. These research projects promote the studies of coupled solid–liquid problems in geotechnical engineering. In recent research, most analyses of coupled seepage and stress–stain fields are based on the effective stress theory. In the calculation of the stress field of rock masses, only the pore hydrostatic pressure is taken into account. As a result, the groundwater action is under-estimated in the stability analysis of rock masses. According to statistical data, more than 90% of the landslides, more than 60% of the mine flooding, and about 30–40% of dam instability are related to groundwater movement. It is difficult to interpret the cause of these hazards by using the analysis of coupled seepage and stress–stain fields based on the effective stress theory. Integrated analysis of the interactions between groundwater and geo-environment should be applied to the analysis of the geological hazards. The objective of this paper is to analyze the mechanism of the interactions between groundwater and geo-environment; to address the hazards due to the interactions between groundwater and geo-environment such as a reservoir-induced earthquakes, landslides, flooding of mines, ground engineering hazards, instability of dams, the collapse of cavities in carbonate and evaporate rocks, land subsidence and earthquakes; and to use the rock hydraulic theory to analyze the earthquake pregnancy laws and the possibility of predicting and controlling earthquakes.

Interaction between the geo-environment and groundwater

Groundwater is as an important geological agent. The interaction between groundwater and the geo-environment on the one hand alters the physical, chemical, and mechanical properties of rock or soil masses, and on the other hand also changes the groundwater itself.
Flowing groundwater causes three interactions with the geo-environment, namely physical, chemical and mechanical. The changes in the geological environment also cause changes in the groundwater system.

The effects of the geological environment on groundwater

The activities of groundwater with physical, chemical and mechanical processes in the geological environment can mobilize matter and heat, transport matter and heat, lubricate discontinuity surfaces in a rock mass, and generate and modify pore pressures.

Physical interaction of the geological environment on groundwater

Physical interaction of the geological environment on groundwater includes lubrication, softening or weakening, and strengthening of bound water. Lubrication by groundwater of discontinuity boundaries in a rock mass such as grain surfaces in soil mass and in unconsolidated sediments or fracture and fault planes in a rock mass, can reduce the friction and strength of soil or rock masses. As rainfall seeps into the rocky slope with discontinuity, this process causes the sliding of the slope and may lead to landslide. Mechanically, the lubrication caused by groundwater can decrease the friction angle and cohesion of soil or rock masses. The process is particularly effective in areas where large variations in precipitation cause fluctuations in the water table. The effect is further magnified due to high pore pressures and reduces frictional resistance to shear displacement.
Softening or weakening of rock or soil masses caused by groundwater is mainly manifested in the changes of physical properties of the filling material between fracture and fault planes in a rock mass. The filling material can have a weakening effect due to the increase of water content. For example, the filling may change from a solid state to a plastic state or even to a liquid state. The weakening phenomena often occurs in the fault zones with the filling materials. Softening and weakening reduces the compressive strength and shear strength of rock or soil masses and decreases the cohesion and friction angle.
Strengthening of bound water in the unsaturated zone is mainly manifested in enhancing the cohesion among loose soil grains. Groundwater in the unsaturated soil or vadose zone is bound water rather than gravity water. Based on Terzaghi's (1925) theory of stress relations in saturated soils, these changes lead to increases in effective stress in unsaturated soils. Interaction between groundwater and unsaturated soils is manifested in increased strength of soil mass. If no water exists in the soil mass, i.e., sand in a desert, the pores of sand soil in the unsaturated zone are entirely filled with air and the air pressure is a positive value. In this case, the effective stress of sand soil is smaller than the total stress of sand soil. Hence, it is loose sand, but after adding some water its strength can be enhanced rapidly. As gravity water occurs in a soil mass, the water action manifests as the weakening of soil mass. This is the reason that optimal soil moisture is sought for engineering construction.

Chemical interaction of the geological environment on groundwater

Chemical interaction of the geological environment on groundwater includes ion exchange, dissolution, hydration, hydrolysis, corrosion, oxidation-reduction, precipitation and ultra-filtration. Ion exchange between groundwater and rock or soil masses is a physicochemical process in which ions and molecules are absorbed on the surfaces of solid substances by physical and chemical forces. Clay minerals, such as kaolinite, montmorillonite, illite, chlorite, vermiculite, zeolite, ferric oxide and organic matter are the most important ion exchange substances due to the colloidal materials of large surface areas. For example, if the groundwater with enrichment in Ca^{2+} and/or Mg flows through a soil mass with enrichment in Na^{+}, Ca^{2+} and/or Mg^{2+}, the groundwater can replace Na^{+} in a soil mass. As a result the enrichment in Na^{+} softens the natural groundwater. Meanwhile, the porosity and permeability of the newly formed Ca^{2+} and/or Mg^{2+}-based clay mineral increases. Ion exchanges between groundwater and rock or soil masses alter the structure and thus affect their mechanical properties.

Dissolution and corrosion play a very important role in the groundwater chemical evolution. The chemical ions in the groundwater are produced by dissolution and corrosion. As the rainfall seeps into the unsaturated soil, it dissolves large amounts of gases such as N_2, Ar, O_2, H_2, He, CO_2, NH_3, CH_4 and H_2S. This process can render the groundwater as weakly acidic and therefore increases the chemical aggressiveness of groundwater. The degree of groundwater dissolution depends on the solubility of the minerals, the antecedent concentration of the groundwater and the geo-environment in regards to certain pressures and temperatures. The weakly acidic groundwater can dissolve soluble rocks such as limestone ($CaCO_3$), dolomite ($CaMgCO_3$), gypsum ($CaSO_4$), halite (NaCl) and sylvite (KCl). The dissolved processes of these soluble rocks increase the concentration of Ca, Mg, Na, K, CO_3, SO_4 and Cl in groundwater. Meanwhile, the processes lead to forming and expanding karst fissures, karst channels and cavities in rock masses. As a result, the porosity and permeability of rock masses increases. For the collapsible loess, the interparticle cementing material, $CaCO_{3,}$ is dissolved and the macroporous structure is destroyed due to the increase of soil moisture. The process causes loess deformation, which is a well-known loess collapse phenomenon. The degree of loess collapse depends on the porous structure, groundwater movement and temperature of the location.

Hydration refers to the process in which water enters the crystal lattices of minerals in rock or soil masses, or the water molecules attach to the ions of soluble rocks. As a result the macroscopic, mesoscopic and microscopic structures of rocks are changed. Hence, the cohesion of rock or soil masses reduces.

Hydrolysis is a chemical reaction between groundwater and the ions of rock or soil. If the cations in rock or soil masses are hydrolyzed, the pH indicator in groundwater increases, i.e., $M^{+}+H_2O=MOH+H^{+}$. As a result, the hydrolysis process enhances the acidity of groundwater. If the anions in rock or soil masses are hydrolyzed, the hydroxyl ion in groundwater increases, i.e., $X^{-}+H_2O=HX+OH^{-}$. Therefore, the hydrolysis process enhances the alkalinity of groundwater. While hydrolysis alters the acidity and the alkalinity of groundwater, it changes the properties of rock or soil masses.

Oxidation-reduction refers to the chemical reaction in which the electrons are transferred from one atom to another. In the oxidation process, the oxidized substance loses free electrons. In the reduction process, the reduced substance gains free electrons. Oxidation and reduction must occur together and also compensate each other. The vadose zone above the water table can be considered as an oxidation zone because there is air and water in the soils. Below the water table in the saturation zone, groundwater is rapidly depleted of oxygen. The solubility of oxygen in the water with 6.6 cm^3 per liter at 20 °C is much lower than that in the air with 200 cm^3 per liter at 20 °C. Therefore, oxidation becomes weak with an increase of depth, while reduction becomes strong with an increase of depth. In the subsurface, oxidation and reduction exist between groundwater and rock/soil. For example, iron sulfide oxidizes to form ferric oxide and sulfuric acid, and carbonate rock corrodes to produce carbon dioxide. Oxidation and reduction not only change their mineral composition, but also alter the chemical composition and aggressiveness of groundwater. Meanwhile, oxidation and reduction affects the mechanical properties of rock or soil masses.

Attack by acids can change the rock framework and increase chemical materials in groundwater. These acids are carbon dioxide (CO_2), nitric acid (NO_2), sulfuric acid (H_2SO_4) and various organic acids. With the increase of human activity, the increase of carbon dioxide and sulfuric dioxide leads to acidic rainfall. As acidic rainfall seeps into the soil or rock masses, the ability of attack by acids in groundwater enhances and affects the mechanical properties.

The above-mentioned various chemical reactions between groundwater and rock or soil masses mostly occur simultaneously, however their reaction velocities are generally very slow. Chemical action mainly changes the mineral composition, alters the structural characters and affects mechanical properties of rock or soil masses.

Mechanical interaction of the geological environment on groundwater

The mechanical effect of the geological environment on groundwater includes hydrostatic and hydrodynamic pressures. The former affects the effective stress and strength of rock or soil masses. The hydrostatic pressure may cause dilatational deformation in the fractured rock or soil masses. The hydrodynamic pressure produces a tangential force which reduces the shear strength of rock or soil masses. As groundwater moves in the loose soil mass, the hydrostatic pressure acts as a surface force and causes a reduction in the effective stress of the soil body. The hydrodynamic pressure acts as a body force exerted on soil particles and causes movement of soil particles and the local destruction of the soil body. This is called the piping phenomenon. Groundwater flow in a crack or a fault of rock mass may produce two forces: one is the hydrostatic pressure perpendicular to fracture walls, another is the hydrodynamic pressure parallel to the fracture walls. The former results in the vertical deformation of the fracture and reduces the compressive strength of rock masses. The latter causes the tangential deformation of fracture and reduces the shear strength of rock masses. The two forces are both surface forces (Wu and Chai 2001).

The effects of groundwater on the geo-environment

Groundwater exists in the geo-environment with geo-stress, geo-thermal and geo-chemical fields. The changes of the geo-environment lead to the pattern change of groundwater flow and transport. Due to the topography, the groundwater flow system is called the gravity-driven system of groundwater. In the recharge areas, the hydraulic heads representing the groundwater mechanical energy, are relatively high and decrease with increasing depth (groundwater flow is downward and divergent). In the areas of throughflow, the groundwater mechanical energy is largely invariant with depth and, consequently, flow is chiefly lateral. In discharge areas, the hydraulic head is low and increases downward, resulting in converging and ascending flow.

The void structures of rock or soil masses control the recharge, flow, and discharge conditions of groundwater in certain geological environments. The void structure changes of rock or soil masses caused by tectonic compression and sediment compaction lead to changes in groundwater flow. The changing geo-stress induced by nature and human engineering affects groundwater flow and pressures in rock or soil masses.

The anomalies of geo-thermal heat and geo-thermal gradients affect the mechanical properties of rock or soil masses and groundwater properties. The thermal convection can drive groundwater flow and transport. The negative anomaly of geo-thermal heat and geo-thermal gradients can lead to descending flow in the geological environment. The positive anomaly of geo-thermal heat and geo-thermal gradients can lead to ascending flow in the geological environment.

Groundwater and rock or soil masses exist in the geological environment. The result of the interactions between groundwater and rock or soil masses causes them to become mutually transformed. Meanwhile, the geological environment is continuously changed in the spatio-temporal domain. Once this change reaches the limit state, geological hazards will take place.

Hazards caused by the interactions between groundwater and the geo-environment

Land subsidence and the collapse of cavities in carbonate and evaporate rocks

Land subsidence is a gradual settling or sudden sinking of the Earth's surface owing to the subsurface movement of the Earth's materials. Land subsidence is a global problem, and in China more than 50 cities such as Shanghai, Tianjin, Xi'an, Wuxi, Changzhou, Ningbo and Datong have been directly affected by subsidence. The types of land subsidence include the compaction of the aquifer system, the drainage of organic soils, the collapse of underground mines, subsidence associated with tectonism, subsidence of thawing permafrost, the consolidation of sedimentary deposits on geologic time scales, the compaction of sediments due to the removal of oil and gas reserves, and subsidence associated with hydrocompaction, natural compaction and sinkholes. More than 85% of the identified subsidence in China is a consequence of the exploitation of groundwater. In many areas of the semi-arid north, and in more humid areas underlain by soluble rocks such as limestone, gypsum, or salt, land subsidence is an often-overlooked environmental consequence of the over-abstraction of groundwater resources.

The hazards caused by land subsidence include the damage of bridges, roads, railroads, storm drains, sewers, canals, levees, buildings and well pipes. In some coastal areas, subsidence has resulted in tides moving into low-lying areas that were previously above high-tide levels. In some cities, such as in Xi'an, Datong and Las Vegas, land subsidence is accompanied by the occurrence of earth fissures. Earth fissures lead to the destruction of roads, the splitting of buildings, damage of underground drainage system, etc. In about 40 cities in limestone regions in China such as Wuhan, Tangshan, Jinan, Qinhuangdao and Guilin, over-abstraction of groundwater has caused ground collapse. All these demonstrate that rock masses are not unchangeable rigid medium, and they interact with groundwater. Under natural conditions groundwater and rock or soil media form a dynamically mechanical balance. Over-exploitation of groundwater causes the decline of the groundwater level in an aquifer system and thereby leads to compaction and can decrease the permeability and porosity of the aquifer system, influence the recharge, flow and storage of groundwater, and finally result in a reduction in water supply capacity of well fields.

The amount of land subsidence includes three aspects, namely, the amount of aquifer-system compaction due to the reduction of groundwater pressure and the increase of effective stress in rock or soil masses, the amount of consolidated deformation of semipervious layers with clay, and the amount of vertical deformation of an aquifer due to the horizontal movement of soil particles accompanied by groundwater flow to wells. In addition, the amount of land subsidence also includes the subsidence amounts associated with ground loads, underground engineering and tectonism.

The mechanism of the collapse of cavities in carbonate and evaporate rocks are of two types, due to groundwater abstraction in karst regions. When a karst aquifer with many cavities in carbonate and evaporate rocks underlies a loose sand aquifer, natural groundwater pressure and stress from rock or soil masses are in a balanced state. As the karst groundwater level drops to below the loose sand aquifer due to groundwater withdrawal, the hydraulic gradient between the upper and lower two aquifers increases. Low hydrodynamic pressure, groundwater, and soil particles in the overlying loose aquifer vertically move to the underlying karst cavities and cause ground collapse. When the overlying loose layer is an impervious clay layer and the underlying layer is a confined karst aquifer with many cavities, the natural karst groundwater pressure and stress from rock or soil masses are in a balanced state. Once the hydraulic head falls below the top of the karst aquifer due to human abstraction of karst groundwater, a vacuum zone may be formed above the unconfined groundwater level in the karst aquifer. As a result, compaction of the overlying loose layer occurs due to the increase of effective stress, and the overlying clay layer moves into the underlying karst cavities. This process results in ground collapse in karst regions.

Land subsidence caused by oil and gas exploitation occurs in oil and gas fields. For example, the amount of land subsidence in the south Belridge oil field in California has reached 2.54 m and the ratio of well failure has reached 3% per year. The maximum amount of land subsidence of Ekofisk oil field in the North Sea of Norway, reached 3.0 m at the time of the discovery of subsidence phenomenon in 1984, and 6.0 m in 1994. The land subsidence rate of Groningen oil field in the Netherlands reached 1.0 m. Land subsidence also occurred to different degrees in some old oil fields in China. Well pipe failure often takes place in oil fields due to land subsidence and the fault sliding caused by water injection. Therefore, a lot of research has paid great attention to these problems.

Land subsidence caused by oil and gas field exploitation is mainly attributed to the reduction of fluid pressure and the increase of effective stress in rock masses, which leads to compaction of the rock framework and compression of fracture and fault zones in rock masses. Accordingly, important subjects in oil–gas field exploitation include the quantitative study of the coupling relationship between multiphase fluid flow and rock deformation in oil–gas basins, as well as the constructed models for coupled fluid-seepage pressure fields, geo-thermal fields, and stress fields in rock masses.

Dam instability

The evaluation of dam stability is important work in water conservancy and hydropower projects. The causes responsible for dam instability are numerous, of which dam failure caused by the interaction between water and rock is one of the most important causes. For an arch dam, the stability of the dam shoulder is of vital importance. For example, Malpasset arch dam, 66.5 m in height, burst in 1959 when water was first stored in the dam. The reason may be that the tensile stress acted on the dam arch and pulled the rock mass around the dam heel. After storing water in the reservoir, seepage took place along the crack. Because the fault of the downstream blocked the seepage water channel, a pore hydrostatic pressure equivalent to the total head of the reservoir formed in the crack. This pore hydrostatic pressure enlarged the crack, and pore hydrodynamic pressure reduced the shear strength of the fault planes. The conjunction of pore hydrostatic pressure and pore hydrodynamic pressure caused dam instability. For the gravity dam, the stability of the dam base is most important. In the study of the influence of water–rock interaction on the stability of a gravity dam base, the uplift pressure of the dam base must be considered. In addition, pore hydrodynamic pressure, pore hydrostatic pressure and the physical and chemical interactions between groundwater and dam base rocks should be taken into consideration. With regard to the existing evaluation method of the stability against sliding, only the pore hydrostatic pressure is considered. In a fractured rock mass, the hydrodynamic pressure produces a tangential force, reducing the shear strength of rock or soil masses. Dam failure is often related to the combined effect of hydrostatic and hydrodynamic pressures.

Reservoir-induced earthquakes

So far, over 100 reservoirs in the world have caused induced earthquakes. More than 20 examples have occurred in China, and an earthquake of the largest magnitude of 6.1 occurred in the reservoir area of the Xinfeng River. A reservoir-induced earthquake may destroy the dam and nearby buildings, even kill people and animals. A reservoir-induced earthquake is the result of the water–rock interaction. Its inducing factors include water load in a reservoir, the increase of hydrostatic and hydrodynamic pressures below a reservoir in an active fault zone, physical and chemical interactions between water and rock, and the thermal disequilibrium within the active fault zone due to the seepage process in the reservoir. The water load in a reservoir enhances the gravity of rock masses in the reservoir area and changes the stress field in the rock mass. As water in a reservoir seeps into an active fault zone, the effective stress in the rock mass is reduced below the reservoir due to the increase of hydrostatic pressure. The shear strength of active fault planes decreases due to hydrodynamic pressure. In an active fault zone, physical and chemical interactions between water and rock lead to a softening in the filling materials that lubricates fault planes and changes structures. These processes decrease the cohesion and friction angle in the fault zone and reduce the shear strength of active fault planes and filling materials. Reservoir water along an active fault produces thermal disequilibrium, leads to the increase of thermal stress in an active fault, and induces water movement toward the low-temperature direction. The above processes may result in the displacement and sliding of an active fault and induce earthquake hazards in the active or potentially active fault zones.

There are three types of hypocenter mechanisms of reservoir-induced earthquakes including: the strike-slip fault, normal fault and thrust fault type. A normal fault is an inclined fracture along which the rocks above the fracture have apparently moved down with respect to those beneath. A thrust fault is an inclined fracture along which the rocks above the fracture have apparently moved up with respect to those beneath. A strike-slip fault is an inclined or vertical fracture along which movement has been predominantly horizontal. According to the analysis of an existing reservoir-induced earthquake, thrust mechanism seldom produces a reservoir-induced earthquake because low permeability in a thrust fault zone reduces the effect of the thrust fault zone on the penetration of reservoir water. Hence, it is difficult to produce the sliding of the fault due to the form of a reservoir. Even if an earthquake occurs in a reservoir, it may be caused by a high natural geo-stress condition. For a normal active fault, a reservoir-induced earthquake can easily take place because high permeability in the fault zone enhances the interaction between the groundwater and the geo-environment. Furthermore, the reservoir water load and the hydrodynamic pressure of groundwater enhance sliding forces of the normal fault. The processes result in the deformation and sliding of an active fault and induce the earthquake. In general, thick filling materials exist in a normal fault zone and the fault plane is declining and indented. In general, the earthquake induced by an active normal fault in a reservoir area has higher frequency and lower intensity. In the earthquake-induced region, the geo-stress is lower due to the antecedent partial release of geo-stress in the active normal fault zone. An active strike-slip fault leads to reservoir-induced earthquakes under the reservoir water load, due to hydrostatic pressure, hydrodynamic pressure, the thermal difference and physico-chemical interactions between the groundwater and the fractured rock mass. In general, filling materials seldom exist in a strike-slip fault zone and the fault plane is steep, even, straight and smooth. An earthquake induced by an active strike-slip fault in a reservoir area has high frequency and intensity due to rapid seepage and high geo-stress in an active strike-slip fault zone. The quantitative analysis of reservoir-induced earthquakes should be based on the geological conditions by using the model for coupled hydro-thermal–mechanical processes in fractured rock masses. The hydrodynamic and hydrostatic pressures, physical and chemical interaction between the groundwater and the geo-environment, and the type of an active fault should be considered in the model for coupled hydro-thermal–mechanical processes.

Landslide

According to statistics, more than 90% of landslides are caused by groundwater seepage. In south China, especially in the upper and middle reaches of the Yangtze River, most of the large-scale landslides are related to rainfall, in particular storm rainfall. Landslides in cold regions of China are closely related to the freeze-thawing process. Landslides in a reservoir region are mostly related to the changes of the reservoir water level.

The interaction between groundwater and rock or soil masses often causes the instability of the slope. The hydrostatic and hydrodynamic pressures in groundwater may play a very important role. According to the analysis of the groundwater recharge, throughflow, and discharge conditions in a slope, the groundwater flow has an unsteady flow due to the recharge of precipitation infiltration. The groundwater hydraulic gradients are smaller than zero ($\Delta H<0$), equal to zero ($\Delta H=0$) and larger than zero ($\Delta H>0$) in the recharge area in the upside of a slope, in the throughflow area in a slope and in the discharge area at the front edge of the slope, respectively. Therefore, the effective stress of the rock or soil masses is larger than the total stress of the rock or soil masses in the recharge area. The groundwater flow in the recharge area in the upside of a slope can enhance the strength of the rock or soil masses. At the front edge of the slope, the discharge region of groundwater flow, rock or soil masses are subject to great hydrodynamic pressure and effective stress. The groundwater flow at the front edge of the slope can reduce the strength of the rock or soil masses. From the groundwater flow view, a slope base is unsafe. The interaction of groundwater flow and the geo-environment may cause the movement of a slope. The movement of a slope can change the recharge, flow, and discharge conditions in the slope, and even lead to the barrage of groundwater flow at the front edge of the slope. When the flux is equal to a constant and the sectional area through which groundwater flow approaches zero, the seepage pressure gradient approaches infinity based on Darcy's law. The large seepage pressure gradient may result in a landslide.

In the upstream and mid-stream regions of the Yangtze River, high and steep slopes were formed by a downcutting riverbed and an uplifting mountain massif due to neotectonic movement. In the region, large landslides often occur due to precipitation, especially storm rainfall. As rainwater rapidly soaks into the slope along fault zones, it causes a rapid rise in the groundwater level in the slope and a rapid increase of seepage pressure at the front edge of the slope. On the other hand, great instantaneous hydrostatic pressure is exerted on cracked walls at the rear side of the slope and causes the dilatation of cracks. The instantaneous slip of the slope decreases the discharge channel of groundwater flow and produces very high seepage pressure at the front edge of the slope. This is the reason why large landslides often occur in rainy seasons in humid regions.

When the reservoir banks consist of low permeability rocks in the reservoir areas and the reservoir water level suddenly falls within a certain time, the groundwater in the slope flows toward the reservoir area and rapidly increases the seepage pressure at the slope of the reservoir bank. The process easily causes the instability of the reservoir bank or a landslide. When the reservoir banks consist of high permeability rocks and the reservoir water level suddenly rises in a certain time, the reservoir water rapidly seeps into the slope and produces very great uplift pressure at the slope base. The process reduces the effective stress of the rocks of the reservoir bank and easily causes the instability of the slope or a landslide.

In the cold regions of north China, landslides associated with freeze-thawing often occur. According to site investigation, spring water exists at the deformed slope base in the regions. As the spring orifices are frozen in winter, groundwater cannot discharge, thus increasing the hydrodynamic pressure of the slope base. Meanwhile, the groundwater level in the slope gradually rises to above the sliding planes. As a result, landslide takes place due to the lubrication of the sliding planes and the increase of seepage pressures. In these regions, large landslides with deep sliding planes below the frozen soil layer often occur in freezing winter periods. Small landslides with shallow-sliding planes above the seasonal frozen soil zone generally occur in the freeze-thawing period in the spring. Landslides may be caused by many factors such as climate, topography, vegetation, geological environment (rock or soil properties, structure, geostress, groundwater, and geotemperature, etc.), and sliding stages (creep, slow sliding, constant-speed sliding and rapid sliding). Some landslides are caused by these factors and others are caused by some governing factors. It should be stressed that groundwater often plays a very important role in landslides and therefore great attention should be paid to this problem.

Geological hazards of underground engineering

Hazards, such as rock burst, gas rush, flooding and the collapse of mines often take place in underground engineering. The flooding of mines and tunnels are mostly caused by the interaction between the groundwater and the geo-environment. Underground excavation modifies fractures and faults (for example, natural impervious faults are transformed into faults with high permeability) and produce new fractures due to stress redistribution. The process enhances the permeability of rocks, changes the natural seepage field and leads to the flooding of mines and tunnels or collapse of mines. As underground excavation is carried out in an aquifer system, this can directly cause the flooding of mines and tunnels. The amount of flooding depends on the permeability of a rock mass and recharge source. Large flooding of mines mostly occurs in the karst aquifer system. As an underground excavation is carried out in impervious or semipervious layers, the flooding of mines and tunnels depends on the distribution of the faults. When a high-permeable layer or aquifer is around the surrounding rock, the excavation easily causes the flooding of mines and tunnels. For example, in the coalfields of north China, a thick-layer Ordovician limestone aquifer is below the Carboniferous coal layers. Large flooding of mines often occurs due to underground excavation. The underground excavation connects the fault and Ordovician limestone aquifer. To predict the position and flux of the flooding of mines, it is necessary to analyze the changes and interactions of geo-stress and groundwater flow fields under an underground excavation.

Rock burst often occurs in the underground engineering (for example, mining engineering, tunnel engineering of railways and highways, and underground plants) of west China. These regions are in the high geo-stress zone where groundwater flow is seldom in the rock masses. The principle of water–rock interaction can be applied to controlling the rock burst. For example, high-pressure water can be injected into the rock masses with high geostress to release the high geo-stress and reduce the rock bursts.

Earthquakes

The earthquake is one of the most impressive geological phenomena and geological hazards. The degree of devastation it brings, the large areas affected, the rapidity of the process, and the imperfection of warnings all show that the power of forces cannot be easily understood. The side effects set off by earthquakes include, for example, landslides, damming of rivers often followed by disastrous floods when the dam is breached, tsunamis, changes in the level of the land, and fire and disease caused by the initial disturbance.

So far, there is still no method to precisely predict an earthquake. However, for shallow-focus earthquakes (less than 50 km), research demonstrates that the fluid pressure accumulated over the fault may have a control effect on the occurrence of fault movement and earthquakes (Hubbert and Rubey 1959; Healy 1975). From existing earthquake knowledge, the interactions among fluid pressure, thermal and geo-stress fields are important factors affecting the earthquake pregnant process. The earthquake pregnant process is essentially the process of accumulated geo-stress in the earth's crust, leading to the compaction of rock masses and the increase of fluid pressure. In an oil field, the process increases the yield of oil wells. When a fault moves, fluid moves downward along the fault and reduces fluid pressure; this process decreases the yield of oil wells. Hence, a short-term prediction concerning the possibility of an earthquake based can be made based on the abnormal changes of the groundwater level in observation wells and abnormal changes of the yield in oil wells.

According to statistical data, the earthquake frequency caused by active normal fault movement is high, but the earthquake intensity is low because fluid movement reduces geo-stress. The earthquake frequency caused by an active thrust fault is low but the earthquake intensity is high because fluid movement enhances geo-stress. The earthquake frequency caused by an active strike-slip fault is high and the earthquake intensity is also high because fluid movement enhances geo-stress. As the geo-thermal anomaly exists in an active fault zone, heat transport can produce thermal stress, enhance fluid movement and fault movement. Therefore, earthquakes easily take place in geo-thermal anomaly regions. However, because the high temperature can change the mechanical properties of rocks from brittle deformation to plastic flow, the earthquake intensity is low in regions such as in the coastal zone around the Bohai Sea of China. Conversely, the earthquake intensity is high due to the brittle failure of rocks in regions without geo-thermal anomaly such as in the Tangshan region of China.

For intermediate and deep-focus earthquakes (50–600 km), rocks should deform by plastic flow rather than by the sudden brittle deformation that is prevalent in the shallow crust. Dobson and others (2002) measured acoustic emission energy during antigorite dehydration in a multianvil press from 1.5–8.5 GPa and 300–900 °C. There was a strong acoustic emission signal during dehydration, and analysis of recovered samples revealed brittle deformation features associated with high pore-fluid pressure. These results demonstrate that intermediate depth (50–200 km) seismicity can be generated by dehydration reactions in the subducting slab.

To effectively predict and control earthquakes, great attention should be paid to the interaction among fluid pressure, geo-thermal and geo-stress fields.

Summary and conclusions

Groundwater is an important geological agent. The interaction between groundwater and the geo-environment can change the physical, chemical and mechanical properties of rock or soil masses. Meanwhile, the interaction can alter the physical and chemical properties of groundwater. In general, three main types of interaction between groundwater and the geological environment are identified in this paper with several special processes for each one. These types include physical interaction with processes of lubrication, softening or weakening and strengthening of bound water, chemical interaction with processes of ion exchange, dissolution, hydration, hydrolysis, corrosion and oxidation-reduction, and mechanical interaction with processes of hydrostatic pressure and hydrodynamic pressure. The interactions between groundwater and the geological environment can affect the deformability and strength of rock or soil masses. The geological process, engineering activity and high temperature can change the geo-stress field, recharge, throughflow and discharge conditions of groundwater. The consequence of interactions between groundwater flow and geo-stress changes the geological environment. Meanwhile, the interaction processes can induce geological hazards such as a reservoir-induced earthquake, landslide, flooding of mines, ground engineering hazards, instability of dams, the collapse of cavities in carbonate and evaporate rocks, land subsidence and earthquakes.

Groundwater in a recharge zone or vadose zone enhances the mechanical property of rock or soil masses, while groundwater in the discharge zone reduces the mechanical property of rock or soil masses. The processes of interaction between the groundwater and the geo-environment can be used to quantitatively analyze the mechanical mechanism of geological hazards. Earthquake pregnant processes and occurrence significantly influences groundwater movement. The abnormal changes in groundwater level as well as the chemical composition in deep wells, water temperature in geo-thermal wells, and yields in oil wells can all be used to predict an earthquake. Water injection into deep wells in an active fault zone can be used to induce the occurrence of lower earthquakes in intensity and to reduce the occurrence of higher earthquakes in intensity.

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References

Aydin A (2001) Fracture void structure implications for flow, transport and deformation. Environ Geol 40(6):672–677

Bai M, Elsworth D (1994) Modeling of subsidence and stress-dependent hydraulic conductivity for intact and fractured porous media. Rock Mech Rock Eng 27:209–234

Bai M, Meng F, Elsworth D, Zaman M, Roegiers J-C (1997) Numerical modeling of stress-dependent permeability. Int J Rock Mech Min Sci 34:446

Dobson DP, Meredith PG, Boon SA (2002) Simulation of subduction zone seismicity by dehydration of serpentine. Science 298:1407–1409

Healy JH (1975) Recent highlights and future trends in research on earthquake prediction and control. Rev Geophys Space Phys 13:361–364

Hubbert MK, Rubey WW (1959) Role of fluid pressures in mechanics of overthrust faulting (1): mechanics of fluid-flow porous solids and its application to overthrust faulting. Bull Geol Soc Am 70:115–166

Ingebritsen SE, Sanford WE (2000) Groundwater in geologic processes. Cambridge University Press, Cambridge, 365 pp

Jing L, Tsang C-F, Stephansson O (1995) DECOVALEX: an international co-operative project on mathematical models of coupled THM processes for safety analysis of radioactive waste repositories. Int J Rock Mech Min Sci Geomech 32(5):389–398

Louis C (1969) A study of groundwater flow in rock masses and its influence on stability of rock masses. Rock Mechanics Report No 10, Imperial College, London, 90 pp

Louis C (1974) Introduction a l'hydraulique des roches. Bull Bur Rech Geol Minier 3–4:283–356

Nagaraj TS, Pandian NS, Narasimha Raju PSR (1994) Stress-state-permeability relations for over-consolidated clays. Geotechnique 46:363–366

Noorishad J (1982) A finite element method for coupled stress and flow analysis in fractured rock mass. Int J Rock Mech Min Sci Geomech 19:185–193

Noorishad J (1989) Coupled thermal-hydraulic-mechanical phenomena in saturated fractured porous rocks: numerical approach. J Geophys Res B12:10365–10373

Oda A (1985) Permeability tensor for discontinuous rock masses. Geotechnique 35:483–495

Oda M (1986) An equivalent continuum model for coupled stress and fluid flow analysis in jointed rock masses. Water Resour Res 22:1845–1856

Snow DT (1968) Fracture deformation and changes of permeability and storage upon changes of fluid pressure. Q J Colorado School Mines 63(1):201–244

Stephansson O (1995) Introduction to special issue on T–H–M coupling in rock mechanics. Int J Rock Mech Min Sci Geomech 32(5):387

Terzaghi K (1925) Erdbaumechanic auf Bodenphysikalischer Grundlage (Geological engineering based on soil-mechanical principles). Franz Deuticke, Leipzig 399 pp

Tsang C-F, Stephansson O (1996) A conceptual introduction to coupled thermo–hydro–mechanical processes in fractured rocks. In: Stephansson O, Jing L, Tsang C-F (eds) Coupled thermo-hydro–mechanical processes of fractured media, mathematical and experimental studies developments in geotechnical engineering, vol 79. Elsevier, Amsterdam pp 1–24

Witherspoon PA, Wang JSY, Iwai K, Gale JE (1980) Validity of cubic law in a deformable rock fracture. Water Resour Res 16:1016–1024

Wu Y (1997) A generalized double porosity media model for coupled stress and seepage fields in fractured rock mass. In: Proceedings of the International Symposium of the Engineering Geology and Environment, Athens, Greece, 23–27 June. A A Balkema, Rotterdam, pp 2913–2918

Wu Y (1998) On mechanical property of rock or soil masses by the action of seepage. In: Proceedings of the 8th International Congress of the International Association for Engineering

Geology and the Environment. A A Balkema, Rotterdam, pp 3481–3486
Wu Y, Chai J (2001) Analysis of seepage forces exerted on fracture network of rock mass (In Chinese). J Eng Geol 1:24–28
Wu Y, Gao R (1997) A continuum model of coupled stress, temperature and fluid pressure fields effect on oil–gas migration (in Chinese). J Xi'an Univ Technol 3:204–209
Wu Y, Gao R (1998) A double porosity media model of coupled stress, temperature and fluid pressure fields effect on oil–gas migration (In Chinese). J Xi'an Univ Technol 2:113–143
Wu Y, Zhang Z (1994) Research on lumped parameter model of coupled seepage and stress field in fractured rock mass. In: Proceedings of the Seventh International Congress of the International Association of Engineering Geology. AA Balkema, Rotterdam, pp 4601–4604
Wu Y, Zhang Z (1995) Introduction to rock mass hydraulics. Southwest Jiaotong University Press, 172 pp
Zhang M, Esaki T, Olsen HW, Mitani Y (1997) Integrated shear and flow parameter measurement. Geotech Test J 20(3):296–303