Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 37 (2013) 3875 – 3882

Energy Procedia

GHGT-11

Assessing the geomechanical responses of storage system in CO_2 geological storage: An introduction of research program in the National Institute for Advanced Industrial Science and Technology (AIST)

Takahiro Funatsu[a], Yasuko Okuyama[a], Xinglin Lei[a], Shinichi Uehara[b], Yoshito Nakashima[a], Takashi Fujii[a] and Shinsuke Nakao[a]

[a]*Institute for Geo-Resources and Environment, GSJ, AIST 1-1-1, Higashi, AIST Central 7,Tsukuba,Ibaraki 305-8567, Japan*
[b]*Faculty of Science, Toho University, 2-2-1 Miyama, Funabashi, Chiba 274-8510, Japan*

Abstract

This paper overviews studies being conducted in the National Institute for Advanced Industrial Science and Technology (AIST) on the fluid-rock mechanical interaction associated with CO_2 geological storage (CGS). Our studies include the extension of TOUGH-FLAC simulator developed in LBNL to CGS under the geologic conditions of Japan where the young sedimentary basins underlain by so-called “soft rocks” are postulated to be the place of CO_2 storage. Experimental studies and basic studies on the petrophysical properties of “soft rocks” are also the important parts of the whole research program to elucidate their mechanical behaviors under the conditions in and around a CO_2 reservoir and its caprock.

Selection and/or peer-review under responsibility of GHGT

Keywords: Geomechanical response; Reservoir-caprock system; Fluid flow-rock mechanical coupled simulation; Rock mechanical experiment; Matsushiro phenomena; Natural analogue

1. INTRODUCTION

The rock-mechanical response of CO_2 storage system (i.e., reservoir and caprock) is a sensitive issue for Japanese CO_2 geological storage (CGS), due to the geologic setting of the Japanese islands as an active island arc. Well before the M9.0 East Japan earthquake on March 11, 2011, the Carbon Dioxide Capture and Storage (CCS) study Group, Ministry of Economy, Trade and Industry (METI), has recommended screening out the areas having detectable faults from candidates of a storage site for planned 10^5t-scale demonstration (CCS Investigation Commission [1]). Another factor to be considered is the inferred complex behavior of so-called “soft rocks” that are the main constituent of Cenozoic strata of

1876-6102
Selection and/or peer-review under responsibility of GHGT
doi:10.1016/j.egypro.2013.06.285

the young sedimentary basins; the Cenozoic basins are considered to be suitable to storage sites in Japanese CGS (Nakanishi et al. [2]). A number of observations in demonstrations in the world report an increase of well bottom pressure, which is an indicative of increasing pore pressure to modify the stress distribution underground. In the famous In Salah case where the storage system is composed of relatively rigid Paleozoic sediments, the change caused rock-mechanical responses including observable uplift around the injection well (Mathieson et al. [3]; Onuma and Ohkawa[4]). The changes were interpreted by the use of numerical simulation through the extension and opening of pre-existing fractures in the storage system associated with an influx of fluid (Smith et al. [5]; Vasco et al. [6]). In soft-rocks, however, laboratory experiments suggest that the increasing pore pressure under confining pressures does not always cause rupture: in some circumstances with increasing pore pressure, the mechanical response ends a collapse of pores to promote total compaction of rocks (Uehara et al. [7]). The different behaviors of soft rocks, namely, to make fractures or to promote compaction, probably lead to a marked difference in rock permeability and total rock volume, and eventually to dynamic behavior of strata themselves. This is an important character of soft rocks and should be taken in consideration for the stability and safety of CO_2 storage system that will be placed in soft bed rocks.

In this paper, we present an overview of on-going researches in the National Institute for Advanced Industrial Science and Technology (AIST) concerning to the fluid-mechanical modeling of soft rocks. Our goal is to make a fluid flow-rock mechanical coupled simulation to be applicable to Japanese soft bed rocks for the assessment of the mechanical behavior of the CO_2 storage system. An extension of TOUGH-FLAC simulator, by the combination of history matching with natural analogue data and rock mechanical experiments, is in the core of our research.

2. EXPERIMENTAL STUDIES

2.1. Experimental studies on rock deformation and deformation-induced permeability changes

Rock mechanical experiments on soft rocks have two principal targets; 1) to investigate mutual relations of fracturing-dominated and compaction-dominated deformation regimes in relation to changes of rock permeability, and 2) to accumulate petrophysical data for the use of fluid flow-rock mechanical simulation. The rock permeability under deformation is investigated by using intact cylindrical mudstone samples sandwiched by pre-cut sandstone plates of high permeability (Fig. 1a). The assembled test piece is set in a pressure vessel, compressed under controlled confining pressures, associated with permeability measurement by the pore pressure oscillation method. The experiments on two types of siliceous mudstone of Hokkaido district clearly indicate the complicated ways of deformation of soft rocks (Uehara et al. [7]). The siliceous mudstone from the Miocene Wakkanai Formation develops a fracture introduced by the deformation of pre-cut planes in the top and bottom sandstone pieces. Associated with fracturing is a marked increase in permeability (shown by a blue line in Fig. 1c). The formation of a new fracture is confirmed by visual inspection and X-ray CT analysis (light-colored region in Fig. 1e). The results clearly show that the fracture acts as a conduit of water and give rise to high permeability of deformed mudstone. Contrary to the Wakkanai mudstone, an obvious failure point was not detected in the case of Pliocene Koetoi siliceous mudstone in a similar compressional test (see the red line in Fig. 1b). The rock permeability decreased slightly with a rapid increase of differential stress, and then kept almost constant (see the blue line in Fig. 1b). The X-ray CT study of the specimen indicates the formation of high-density region in its center (the dark-colored part in Fig. 1d). The observed change suggests a collapse of preexisting pores to make a “barrier” for water permeation. Since these two mudstones are chemically equivalent, the different behaviors in rock mechanical experiments are interpreted by the differences in petrophysical and microstructural properties of the original siliceous mudstone. The experimental study is continuing so as to find critical factors controlling the two different ways of fluid-rock mechanical behaviors of soft rocks. The fluid-rock mechanical behaviors in the presence of CO_2-H_2O fluid are also under investigation.

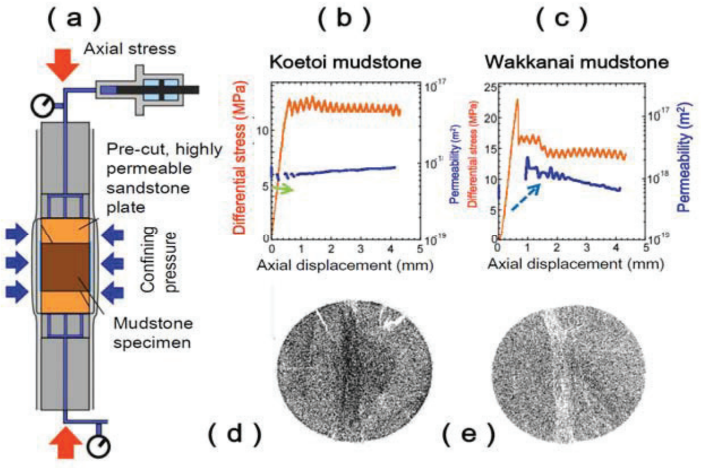

Fig. 1. (a) Outline of experimental setup after Uehara et al. [7]. The figures 1b and 1d show results on geologically young Koetoi mudstone, whereas 1c and 1e show the results on older Wakkanai mudstone. (b) Changes in permeability (blue line) of Koetoi mudstone under increasing differential stress (red line). (c) Changes in permeability (blue line) of Wakkanai mudstone under increasing differential stress (red line). (d) X-ray CT image of the central part of Koetoi specimen. (e) X-ray CT image of the central part of Wakkanai specimen.

2.2. Experimental studies on rock mechanical and petrophysical properties

Our rock mechanical studies provide scientific supports to on-going 10^5t-scale demonstration in Tomakomai, Hokkaido district, North Japan. Under the supervision of METI, technical assessment of the JCCS Tomakomai demonstration was carried out in the summer of 2011. Core analyses recovered from the wells in the proposed area for demonstration was carried out in RITE SuperLabo and found that the samples contain numerous minor fractures that can be detected not only by visual inspection but also by X-ray CT scanning. Following to the core analyses, we carried out rock mechanical investigation to obtain frictional strength of three types of rocks from possible storage system in the Tomakomai demonstration. A multi-step frictional test to a single core specimen provided sufficient data to obtain frictional strength of the specimen, which is a critical parameter in the evaluation of fracture development under the conditions postulated to CO_2 storage system in the Tomakomai area. Our experiments have also presented a method to obtain an amount of data from limited number/volume of core specimen for the purpose of technical assessment.

3. SIMULATION STUDY

3.1. Strategy

The rock-mechanical response of CO_2 storage system has been studied intensively in these days so as to make clear the observed responses such as surface deformation (e.g., Onuma and Ohkawa [4]). The coupled fluid flow-rock mechanical simulation is a representative tool for this purpose and the TOUGH-FLAC simulator developed in LBNL (Rudqvist et al. [8]) is becoming a promising one as shown by pilot studies (Todesco et al. [9]; Cappa et al. [10]). The simulator could also be effective to find sustainable injection rate of CO_2 avoiding drastic responses (Rudqvist et al. [11], [12]). In collaboration with LBNL, we began to study TOUGH-FLAC simulation, keeping in mind its application to the geologic conditions of Japan. The core of the work is to introduce into the simulator the numerical relations depicting changes in permeability and stress-strain relations of soft rocks. Rock mechanical experiments on soft rocks under fluid-saturated conditions are necessary for this purpose. In history matching, which is also necessary in simulation study, we decided to use natural data on ground motion and CO_2 leakage that were observed during 1965-1967 Matsushiro earthquake swarm (hereafter refers to Matsushiro phenomena). This is because of the lack of information on the rock mechanical responses associated with fluid leakage in CCS demonstrations in soft bed rocks (e.g., Sleipner area). In addition to an extensive earthquake swarm of more than 140,000 events, the Matsushiro phenomena were characterized by the surface uplift as large as 75 cm, the appearance of a new fault (so-called the Matsushiro fault), and the discharge of ca. 10^7 t of brine containing a large amount of CO_2 (Ohtake [13]; also see Cappa et al. [10]). The Matsushiro phenomena were once studied by Cappa et al. [10] to which we consider needs of improvement of hydrogeologic model.

3.2. Hydrogeologic modeling and the conditions of the preliminary simulation

Cappa et al. [10] treated the subsurface area of 100 x 100 x 6 km having the Matsushiro area in its center by a flat two-layered hydrogeologic model composed of a rigid basement and a mechanically “soft”, overlying cover. The model system also includes two faults crossed in right angles; they are the Matsushiro fault and the Northern Boundary Fault of the Nagano basin (NBF) which is an active fault caused 1847 Zenkouji earthquake. The improvement of our model is as follows; 1) the reduction of the model area to 20 x 20 x 6 km in size (Fig. 2a) considering the geologically and petrophysically complicated nature of the area (Geological Survey of Japan [14]) treated by Cappa et al. [10], 2) incorporating a three-layered structure revealed by repetitive seismic survey after the Matsushiro phenomena to the year of 2002, and 3) incorporating the Southeastern Boundary Fault of the Nagano Basin (SEBF) instead of NBF (Fig. 2a). Our small-scaled model corresponds to the central part of the Cappa et al.’s model and fully covers the area having observed the surface uplift during the Matsushiro phenomena (Kanjo [15]). The model scale seems to be appropriate considering the areal extension of geomechanical effects observed in In salah (Onuma and Ohkawa [4]). The three layers are assumed to have Vp of 6.0, 4.5 and 3.0 km/s, respectively, considering the results of seismic observations. The replacement of NBF by SEBF is based on the observed distribution of hypocenters and surface uplift which extend along SEBF but not along NBF (Ohtake [13]). The SEBF is a geologic fault: the 3-D structure from the seismic survey strongly supports its presence although seismically dormant.

The hydrogeologic model was constructed by numerically combining and extrapolating geology on the cross sections obtained from seismic surveys, well data and 1:50,000 geologic maps, by using GoCAD software (Fig. 2b to d). The complicated geology of the study area is simplified into three major units to

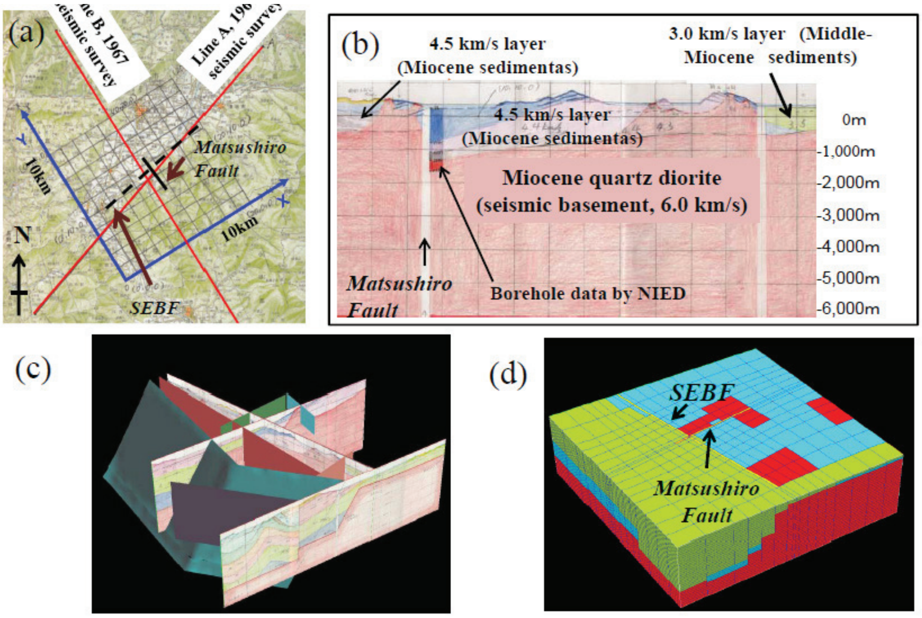

Fig. 2. (a) Plane view of the modeled area shownin X and Y axes and grids. The Matsushiro Fault and the Southeast Boundary Fault of the Nagano Basin are shown in black lines. The red lines indicate the positions of observation lines in 1967 explosive seismic study. (b) A part of 1:1 geologic cross section along a line A viewed from north. The figure also shows three-layered velocity structure on the basis of seismic and stratigraphic data. (c) A panel diagram using various geologic cross sections to form 3-D geologic model. (d) Three dimensional geologic model of the area shown in Fig. 1a (viewed from northwest). The top of the model is set at the sea level.

become concordant with the areal Vp distributions. Our model thus obtained (Fig. 2d) is characterized by an inclined seismic basement (6 km/s layer) from SEBF to the NW direction. The model is essentially three-layered and two-layered ones in the NW and SE of SEBF, respectively. The Matsushiro fault is placed near the center of the model crossing ca. 85 degrees to SEBF (Fig. 2d). Its arrangement of Matsushiro fault is asymmetric against SEBF, extending 5 km to the south and 2 km to the north of this fault. This arrangement is based on the observed asymmetric pattern of surface uplift (Kanjo [15]). This arrangement of Matsushiro fault is also different from that employed in Cappa et al [10].

Because of distinct differences in model between this study and Cappa et al. [10], the hydrogeologic parameters (i.e., porosity and permeability) and rock mechanical parameters (i.e., Young's modulus, Poisson's ratio etc.) in the preliminary simulation conducted in the year of 2011were assumed to be basically similar to those used in Cappa et al. [10], so as to study the effect of the difference of model itself. Parameters for the second layer of the three-layered region in the model were calculated from those in Cappa et al. [10] to become proportional to Vp^2. Other conditions such as the thermal conditions in the model and injected fluid, initial fluid pressure regime within the model, point of fluid injection and so on are set similar to those in Cappa et al. [10]. The fault region is expected to behave elastoplastic whereas the matric properties are assumed to be elastic. The regional stress is arranged to be maximum compressional in E-W and minimum compressional in S-W directions as shown in Fig. 4a.

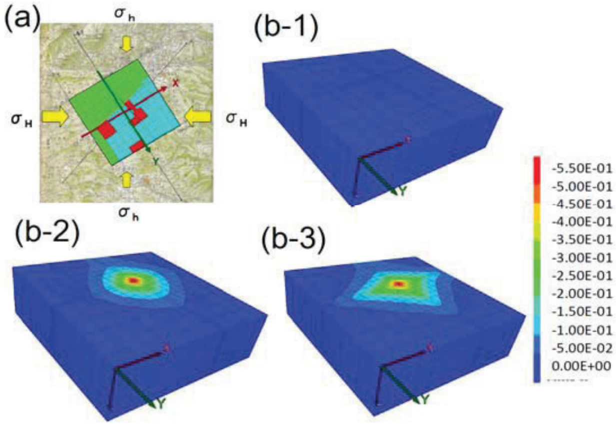

Fig.3 (a) Plane view of the simulation model placed on the topographic map. Two major faults are shown by red lines on the top of the model. Yellow arrows in the figure indicate the directions of regional stress. (b) The results of TOUGH-FLAC simulation. Figures b-1, b-2 and b-3 depict the calculated distribution of vertical motion on the top of the model at the beginning of calculation (i.e., no motion), 1 year after, and 5 year after, respectively. The negative values mean uplift in these figures. The inset in the right of Fig. 3b-3 indicates the scale.

3.3. Results of preliminary simulation and suggested points of further improvement

The preliminary simulation calculated the 3-D distributions of several features including the surface motion. The calculated uplift (Fig. 3b) is as high as 55 cm after 1 year from the beginning of calculation, or fluid injection. The calculated uplift we consider is comparable to the observed one during the Matsushiro phenomena (Fig. 4a, b).

The calculated surface uplift becomes asymmetric to SEBF, which is a difference as compared to the result of Cappa et al. [10]. The asymmetric distribution of surface uplift is concordant with the observation (Fig. 4a). The calculated uplifte gradually enlarges away from the cross point of two faults along their extensions in a skewed rhombic pattern (Fig. 3b-3, 5 years after the beginning of calculation). This indicates that the surface uplift is firstly controlled by the fault arrangement in the model, which is probably related to selective fluid flow in permeable fault zones.

The effect of geologic structure is partly recognized as an asymmetric distribution of moderately uplifted area (the green-colored part in Fig.1b-3). However, we consider that the effect of geologic structure of the model itself must be studied more because we used an almost similar set of fluid-rock parameters to Cappa et al. [10]. We difficult to recognize separately from that of the asymmetric arrangement of Matsushiro fault. The parameters used this former study do not seems to be adequate for the modeling of real natural (and artificial) phenomena. For an instance, the values of Young’s modulus we (and Cappa et al. [10]) used are too low when we consider the numerical relation,

$$E_D = \{(1 + \nu)(1 - 2\nu)/(1 - \nu)\}\rho V_P^2 \quad (1)$$

where E_D, ν, ρ, and V_P represent dynamic Young's modulus, Poisson's ratio, density and V-wave velocity. The accumulation of rock mechanical parameters are absolutely necessary for our further simulation study using the Matsushiro phenomena as a natural analogue of the mechanical response and leakage associated with CGS.

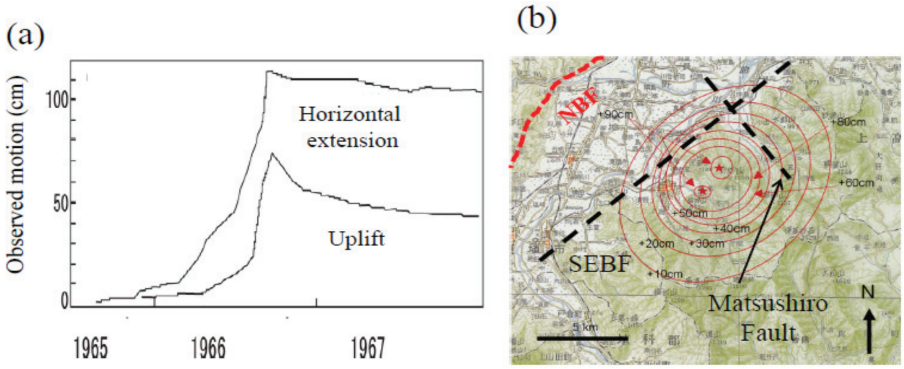

Fig. 4. Observed ground motions during the Matsushiro phenomena. (a) Horisontal extension and uplift from August, 1965 to the end of 1967. (b) Plane view of the areal distribution of the maximum uplift after Kanjo [15]. The major two faults are shown in black lines. The red shaded line represents the trace of Northern Boundary Fault of the Nagano Basin (NBF).

4. CONCLUDING REMARKS

Because of tectonic settings of the country, it is necessary for Japanese CCS technology to evaluate rock mechanical responses of the storage system for the safe deployment and social acceptance of CGS. The technology is also important for the assessment of sustainable injection rate avoiding significant potential rock-mechanical problems. For this purpose, we are studying TOUGH-FLAC simulation in collaboration with LBNL. The principal field of collaboration lies in the extension of the simulator to CCS in soft bed rocks. The research, through the combination of natural analogue study and experimental study on soft rocks under the reservoir conditions, is in progress to the final goal of successful fluid flow-rock mechanical coupled simulation applicable to CGS in our country. Experimental and modeling studies of rocks in the pre-failure stage (Funatsu and Shimizu [16]), studies on the induced seismicity associated with water injection and on fracture sealing by carbonate precipitation are also the elements of our research to the better understanding of the processes associated with the motion of CO_2-rich fluid underground.

Acknowledgements

This research is funded and supported by The R&D programme for the Safe Deployment of CO2 Capture & Storage under the supervision of METI. We are also financially supported by AIST Grant No. AAZA01010X0. We would like to express of our thanks to Dr. K. Kahihara of the JAPEX Research Center for intensive discussion during the simulation work.

References

[1] CCS Investigating Commission. *For the safe deplotment of a large-scale CCS demonstration*.The Ministry of Economy, Trade and Industry; 2009.

[2] Nakanishi, S, Mizuno, Y., Okumura, T., Miida, H., Shidahara, T., Hiramatsu, S. Methodology of CO_2 aquifer storage capacity assessment in Japan and overview of the project. *Ener Proded* 2009; **1**, 2639-2646.

[3] Mathieson, A., Wright, I., Roberts, D., Ringrose, P. Satellite imaging to monitor CO_2 movement at Krechba, Algeria. *Ener Proced* 2009; **1**, 2201-2209.

[4] Onuma, T, Ohkawa, S. Detection of surface deformation related with CO_2 injection by DInSAR at In Salah, Algeria. *Ener Proced* 2009; **1**, 2177-2184.

[5] Smith, J., Duracan, S., Korre, A., Shi, J.-Q., Sinayuc, C. Assessment of fracture connectivity and potential for CO_2 migration through the reservoir and lower caprock at the In Salah storage site. *Ener Proc* 2011; **4**, 5299-5305.

[6] Vasco, D.W., Rucci, A., Ferreti, A., Novali, F., Bissel, R.C., Ringrose, P.S., Mathieson, A.S., Wright, I.W. Satellite-based measurements of surface deformation reveal fluid flow associated with the geological storage of carbon dioxide. *GRL* 2010; 37, L03303, doi10.1029/2009GL041544,2010..

[7] Uehara, S., Takahashi, M., Oikawa, Y., Masuda, K. Depth dependency of fracture permeability in Neogene mudstone. *Abstr AGU fall meeting* 2009..

[8] Rutqvist, J., Wu, Y.-S., Tsang, C.-F., Bodvarsson, G. A modeling approach for analysis of coupled multiphase flow, heat transfer, and deformation in fractured porous media. *Int J Rock Mech Min Sci*, 2002: **39**, 429-442.

[9] Todesco, M., Rutqvist, J., Chiodini, G., Pruess, K., Oldenburg, C. Modeling of recent volcanic episodes at Phlegrean Fields (Italy): Geochemical variations and ground deformation. *Geothermics* 2004: **33**, 531-547.

[10] Cappa, F., Rutqvist, J., Yamamoto, K. Modeling crustal deformation and rupture processes related to upwelling of deep CO_2-rich fluids during the 1965-1967 Matsushiro earthquake swarm in Japan. *JGR*, 2009: **114**, B10304, doi:10.1029/2009JB006398.

[11] Rutqvist, J., Birkholzer, J., Cappa, F., Tsang, C.-F. Estimating maximum sustainable injection pressure during geological sequestration of CO_2 using fluid flow and geomechanical fault-slip analysis. *Ener Covers Manage*, 2007: **48**, 1798-1807.

[12] Rutqvist, J., Birkholzer, J.T., Tsang, C.-F. Coupled reservoir-geomechanical analysis of the potential for tensile and shear failure associated with CO_2 injection in multilayered reservoir-caprock system. *Int J Rock Mech Min Sci*, 2002: **45**, 132-143.

[13] Ohtake, M. A short review of Matsushiro earthquake swarm; looking back 10 years of its cessation (in Japanese). *Kagaku*, 1976: **46**, 306-313.

[14] Geological Survey of Japan. 1:200,000 seamless geologic map of Japan. http://riodb02.ibase.aist.go.jp/db084.

[15] Kanjo, K. Rising process of extruded water that generates the Matsushiro swarm earthquakes: Crustal movement observed from the leveling and water tube tilt meter (in Japanese). *Earth Monthly*, 2004: **28**, 823-830.

[16] Funatsu, T., Shimizu, N. Numerical Simulation of crack propagation in rock by clumped particle model. *Abstr 2011 ISRM Meeting (Beijin)* 2011.