Quantitative simulation of silica scale deposition from physical kinematics perspectives

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Silica scaling restricts the heat extraction and deteriorates the power generation efficiency in geothermal systems. Although drug injection and pH adjustment are practiced in various fields as a countermeasure against this problem, they are still in a stage where trial and error are repeated. The main obstacle of this problem is that the mechanism of silica scaling has not been revealed yet.
In order to predict silica scale precipitation and establish an effective countermeasure means, it is indispensable to construct a numerical calculation model. However, scale deposition phenomenon consists of some processes in which a wide variety of physical and chemical elements are intertwined complicatedly, so that the way to find a method leading to elucidation of its mechanism is extremely steep. There have been a large number of studies on silica scale deposition rate, but order of magnitude difference is pointed out between experimental data and predicted value gained from simple chemical kinetics. Several other contradictions are reported when we analyze the scale deposition process from a chemical point of view, so detailed analysis incorporating new elements is required.
As a part of a novel initiative, Mizushima *et al.* (2016) proposed a scale precipitation prediction method that took physical factors into account, and reproduced the increase of local scale deposition depending on fluid flow velocity.
In our research, we propose a complementary method which enables more accurate prediction of silica scale deposition by introducing several physical actions which were not completely considered in the simulation method constructed by Mizushima *et al.* (2016). We regard the silica involved in scale deposition as spherical colloidal particles and evaluate the mechanical balance in the process where the silica particles flowing in the medium fluid adhere to the wall surface and the condition in which the particles once attached to the wall surface peel off again. We perform direct numerical simulations by making discretized motion equation for individual particles in fluid and the equation considering the rotational moment balance for the particles on the wall surface. With this direct numerical analysis, it is possible to track the particle behavior stably without any restriction due to the grid intervals.
We applied all possible physical kinematic effects to a fine particle including drag force by fluid, gravity, buoyancy force, Van der Waals attractive force, electrostatic repulsive force, and Brownian motion, which is dominant in the diffusive behavior of particles. We set a 2D parallel plate channel with and without the slip flow condition. In the process of particle adhesion to the wall, we calculate particle motion by setting particle arrangement. Particles are moved in the fluid by diffusive effect mainly based on Brownian motion till they reach the wall vicinity where adhesive force is dominant. In the process of particle detachment from the wall, we evaluate the moment balance with random elements and count the number of particles peeling off the wall. The final scale deposition rate per unit surface area was given by using 100,000 realizations.
Our simulation results of silica deposition rate show good agreement with the experimental data (Hosoi and Imai,1982). Furthermore, our analysis of the shear flow effect on the detachment of deposited particles makes it possible to explain the trend of field observation (Mercado *et al.*, 1989). It is a remarkable achievement in this research that we elucidate once again the necessity to incorporate the physical process into the prediction of scale deposition. Since our quantitative simulation has wide expandability, the proposed method can be a novel tool to evaluate the influence of particle deposition in not only geothermal systems but also oil and gas fields.

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Keywords: geothermal energy, scale, silica scale

Fundamental study for estimating azimuthal shear wave anisotropy by applying VSM in marine airgun survey

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Recently, shear wave explorations have been conducted to obtain not only geological structure but also lithological properties of subsurface materials. Although the utilization of shear wave has been drawing the attention, it has been thought difficult to use shear waves in the marine environment due to the lack of shear modulus in water. Some shear sources have been developed for the use in water, they were assumed to use stingers to sub-seafloor or to have surface directly contacting seafloor material that would raise the time cost of survey or risk environmental impact in the utilization.
In the present study, we apply the virtual source method originally proposed by Bakulin et al. (2004) to overcome the existing problems of time cost and environmental impact to exploit the use of non-contact seismic sources in the marine environment. We improved the virtual source method (VSM) to virtually enable the emission of shear waves in water even for air-gun shot records so that the estimation of shear wave structure in the subsurface becomes possible. We confirmed the effectiveness of the proposed approach using a synthetic seismic data set produced by a 3-dimensional finite-difference simulation with the rotated staggered grid. We set a single ocean bottom seismogram (OBS) on the seafloor and an array of explosive acoustic sources in water beneath the surface. In the subsurface, an anisotropic and an isotropic layers are alternately stacked as a geological model. The azimuthal directions of 45- and 60-degrees of anisotropic layers of horizontal axes of symmetry to the survey line are assumed. It has been proved that the application of our VSM and the Alford rotation could lead us to the assumed azimuthal direction in the subsurface for about two third of the shot locations in the survey line.

Keywords: VSM, Seismic interferometry, S-wave survey, marine survey

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AVO analysis using horizontal component of seismic data in equivalent offset migration method

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On exploring subsurface resources such as oil or natural gas reservoirs, seismic reflection survey has been widely implemented in order to image subsurface structures. In recent years, utilization of S-wave or converted wave is required for estimating lithology or petrophysical properties of reservoir rock. However, such an analysis of S-wave seismograms had been relatively difficult. On the other hand, equivalent offset migration (EOM) proposed by Bancroft et al. (1998) is one of the prestack time migrations and has been found to be effective method for imaging S-wave information on the common scatter point (CSP) gather with recorded horizontal component in our previous study. Furthermore, S-wave AVO effect has also been confirmed by the amplitude reversal of S-wave event on the CSP gathers.
Therefore, we propose the procedure of accurate estimation of densities and shear modulus with S-wave source. First, we conduct numerical experiment with a 2D layer model using horizontal point force to obtain horizontal component seismic data, in which we can get higher S/N data about S-wave. Second, we implement EOM with those data to get CSP gather, and calculate each cross-correlated value versus incident angle as observed waveform information. Third, in contrast, we generate calculated waveform information as a function of incident angle and physical properties with geometrical spreading, radiation pattern and S-wave reflection coefficient. Finally, we can estimate the optimal solutions by minimizing the misfit from the both information.

Keywords: AVO analysis, Equivalent offset migration, Common scatter point gather

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Numerical analysis of passive seismic emission tomography method using oscillation caused by multiphase flow

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Recent years, passive seismic emission tomography, which utilizes seismic signals induced by fluid flow inside reservoirs, has drawn attention to visualize the subsurface. For example, Ted et al. (2016) use the oscillation caused by the oil flowing in the production well to estimate the position of the production well. They detect production well correctly even in the noisy situation near the highway. They conclude that in future they might be able to detect the location of cracks, through which fluid pass through, created by hydraulic fracturing. In addition, Erokhin et al. (2014) estimates the reservoir’ s location and extent using a long period of time records on surface receivers. However, these attempts are experimental, and it is not sufficient to theoretically elucidate the mechanism of oscillation caused by fluid flowing. In this study, we calculate two-phased flow i) oil-water flow model and ii) gas-oil flow model using Lattice Boltzmann Method (LBM) to observe oscillation caused by fluid flowing. LBM is a method to simulate Newtonian fluid with collision models such as Bhatnagar-Gross-Krook. We adopted LBM because it is good at parallel calculation and it can easily deal with multiphase flow. After calculating the seismic waves caused by the stress disturbance occurred in the pore throat using LBM, we calculate waveforms at receivers using the wave propagation solution using Green function under the assumption of isotropic homogeneous medium.

In oil-water flow model, we detect induced waveform with the maximum amplitude of about 30 Pa when an oil droplet passes through the pore throat. On the other hands, we detect 250 Pa of maximum amplitude when a gas bubble passes through the pore throat. Since we can observe the substantial changes of received waveforms due to the difference of fluid property, it suggests the possibility to estimate the change in the properties of the fluid in the reservoir from the observed micro seismic waves. Using those micro seismic waves, we estimate the location of the reservoir. Next, we record micro seismic waves while the reservoir size is gradually expanded. As we change the using record duration for estimate reservoir location, the estimated result is changed and it was consistent with the simulation model. This result shows the effectiveness of PSET using fluid flowing for monitoring reservoir which is producing oil.

Keywords: Passive seismic, LBM

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The effect of flowing small particles on flow characteristics and closure of pore in porous media

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In the production of fluid resources from subsurface reservoir, sanding is the most problematic phenomena which could prevent effective production and sometimes chokes the flowline. The cause of the phenomena is thought as the detachment of sand particles in the matrix of formation to flow into pores of reservoir. These sand particles reduced the permeability of porous flow in the formation and could result in the decrease of production. To evaluate "sanding", it is needed to find the mechanism of this. But it is difficult because many factors affect this phenomenon, e.g. fluid viscosity, shape of sand particles. So, we investigate the mechanism of "sanding" using numerical simulations.
We investigate the effect of some factors; viscosity of flowing fluid, shape of sand particles, and the velocity of fluid. We found that permeability is dramatically decreased by closure of fluid pass when high viscous fluid flows in porous media. In terms of the shape of sand particles, square grains suppress the probability of closure of flow pass because square particles can change the length of particle orthogonal to flow direction by rotation. On the other hand, the velocity of fluid does not affect the decrease of permeability and the probability of closing so much. The decrease of permeability is almost the same among all velocity situations.

Keywords: permeability, sand particles, particle method

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Fundamental research on the role of differential stress in hydraulic fracturing in strength-anisotropic medium

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Hydraulic fracturing is a technique to enhance the permeability around the borehole to create fracture networks in oil and natural gas reservoirs. Since the performance of hydraulic fracturing is not fully predictable beforehand, it is important to pre-estimate the extension and the connectivity of artificial fractures for a given condition such as in-situ stress and various mechanical properties of reservoir rock. It, therefore, has been drawing attention to achieve this with a method of numerical simulation in recent years.
Although microscopic failures and propagation of cracks are known influenced by the ratio of the maximum to the minimum radius of spherical elements, the viscosity of injected fluid, the existence of natural fractures, etc., the propagating direction of hydraulic fractures is in the direction of horizontal maximum stress in an isotropic medium. Since reservoir rock of shale oil or gas is anisotropic in the mechanical properties inferred from several laboratory tests, the propagating direction of hydraulic fractures is known strongly affected by the direction of anisotropy axis. Since there is few researches conducted on the numerical simulation of hydraulic fracturing in strongly anisotropic media with the existence of differential stress towards the borehole, it is necessary to examine the role of the differential stress. We give mechanically anisotropic properties such as uniaxial compressive strength, uniaxial tensile strength, permeability, etc., based on the calibration of microscopic parameters of DEM to represent macroscopic parameters of the reservoir rock. The empirical assumption of macroscopic uniaxial tensile strength distribution is introduced into microscopic strength of the model. Contact and bond forces are given to neighboring particle elements in the model, and both tangential stresses from interstitial fluid are applied to each particle.
The result showed that if the differential stress is large, hydraulic fractures tend to propagate in the direction of maximum principal stress whereas hydraulic fractures tend to propagate in the direction of bedding plane under low differential stress.
Moreover, this information suggests that in the shale reservoir, which has mechanical anisotropy, the differential stress has important role in estimating the propagation direction of hydraulic fractures.

Keywords: distinct element method, hydraulic fracturing, strength anisotropy, shale

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Development of Phased Array Ground Penetrating Radar for near surface exploration

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A portable and non-destructive geophysical tool, Ground Penetrating Radar (GPR), enables us to quickly detect the objects in the shallow subsurface such as cavity, electric cables or water pipes. It is increasingly applied for preventing near surface hazards. Although the resolution of GPR under the antenna is generally very high, the resolution out of the survey lines is depending on the shape of the antenna. We have recently introduced a phased array antenna as a new radar source to overcome this problem (Kikuchi *et al.*, 2016). We showed that comparing with the conventional dipole antenna, the phased array antenna increased the signal-to-noise ratio in observed data resulting from heterogeneity of subsurface and it improved the migration results for the reflectors located lateral to the survey line. However, the coupling effect between array antennas on generated waveform was not taken into consideration. In this study, we calculate the mutual impedance to evaluate the mutual coupling of the array to determine the suitable antenna arrangement. Then, we conducted some GPR surveys in more practical conditions. We use a FDTD method to simulate the propagation of electromagnetic (EM) wave field. Kirchhoff migration method is used to make a 3-D image of subsurface. Our results show that the phased array antenna provides more reliable migration results compared to the dipole antenna we have designed. We conclude that our developed new GPR has an advantage in detecting objects between the survey lines or under the surface structures where we cannot draw a survey line. This will surely lead to the reduction of the cost of GPR surveys.

Keywords: Ground Penetrating Radar, mutual coupling

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Walkaway surface wave survey: a new method for obtaining wide frequency band phase velocities utilizing walking noises along a linear seismic array

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We propose a new passive seismic survey method for obtaining phase velocity curves of Rayleigh waves in a wide frequency band utilizing walking noises along a short-spacing linear seismic array. The method is featured as a technical extension of "hybrid surface wave survey method" we proposed in 2014, and is originated from the passive surface wave survey method named "Linear Array Microtremor Survey" (LAMS), also proposed by the last author in 2011. In the LAMS, spatial autocorrelation (SPAC) analysis is employed for the calculation of a dispersion curve for an arbitrary pair of seismic records estimating random or isotropic microtremor source. Furthermore, the linear array or setting a number of geophones along a line enables us to obtain more accurate phase velocity curves by applying common midpoint spatial autocorrelation (CMP-SPAC) analysis proposed by the third author in 2015. The hybrid surface wave survey is characterized as the combination of active and passive surface wave survey simultaneously conducted along the same seismic line. A number of geophones, set along a line at 0.5 to 2 m intervals, are used to record active surface hitting waveforms and passive microtremor. Two dispersion curves, one is for a higher frequency part calculated from common midpoint cross-correlation (CMP-CC) analysis to active survey records, and the other is for the lower frequency part calculated from passive data applying CMP-SPAC analytical method, are combined to form a single dispersion curve for a specific CMP in a survey line. The method enables us to reconstruct a dense 2D S-wave velocity profile along a line up to 50 m in depth or more using conventional 4.5 Hz geophones. One of the advantages of hybrid surface wave survey is its robustness to the traffic noises or positive utilization of them vice versa. It means it is more suitable for the method to set the line along trunk, heavy traffic highways. We have conducted hybrid surface wave surveys along operational highways which had traffic flows of 300 to 1,500 vehicles per hour. During the field tests, we found a more effective noise source. That is, random walking but along the survey line. We could efficiently obtain wide frequency band dispersion curves emulative to both active and passive survey, only from passive seismic data including noises generated by waking along the survey line. The method is expected to expand the surface wave survey for delineating high-resolution 2D S-wave velocity structure in large urban areas.

Keywords: surface wave, passive seismic, linear array, walkaway noise

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Repeatability of time-lapse measurements using ACROSS in Saudi Arabia

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Introduction

To do the time lapse for monitoring of injected CO_2 in CCS (carbon capture and storage) and EOR, we have used the ACROSS (Accurately Controlled and Routinely Operated Signal System) methodology to monitor the change of subsurface (Kasahara *et al.,* 2010; Kasahara and Hasada, 2016). To evaluate the true subsurface change, it is necessary to clarify the repeatability of the measurement system including instrumental parts of seismic source and receivers. Many factors contribute to repeatability of observation; seismic source signature, ground coupling of source and/or receivers, fixing accuracy of source and/or receiver locations, media along paths, and true subsurface changes (Kasahara and Hasada, 2016). In this presentation, we will examine the repeatability of our measurements by the field data in Saudi Arabia.

We used data obtained by 30 seismic stations in Al Wasse field in 2013–2014 and 2015. In addition, we carried out the refraction survey using the ACROSS seismic source. In the source-gather records the first arrivals decayed at the offset distance further than 700 m. This is thought to be caused by velocity inversion just below the top layer. The characteristics of weak first arrivals at the distance around 500–700 m might affect the repeatability

NRMS Repeatability

Kragh and Christie (2002) proposed NRMS for the repeatability between two traces. If two traces are uncorrelated, the NRMS error is 200%. If one of the traces has half amplitude of the other, the NRMS is 66.7%. In the case of the Gulf of Mexico, the best values were 18–30% (Kragh and Christie, 2002). Eiken *et al.* (2003) obtained approximately 40% NRMS by two surveys with 25 m lateral offset. For most of 4D survey, 10–30% is thought to be a typical good value (Johnston, 2013).

Results of repeatability estimation

We examined the NRMS repeatability using a geophone in the ACROSS source room. Though the analyzed duration is short, the NRMS during 12 days were less than 2%. We can clearly identify daily variations in this source room data possibly caused by housing deformation due to the large variation of outside temperature. The source was in the desert area in winter and the outside temperature was so low during nighttime.

Next, we calculated the travel time variation (dT) and the amplitude variation (dA) for the field stations using the cross-correlation of P-wave portion. The dT and the dA in some stations show small temporal variation during two periods with about two-years interval. We also calculated NRMS using the same P-wave portions. NRMS variation of the stations #33 and #53 were smaller than 5% in the first and the second periods, and it is similar results seen in dT and dA.

Considering the NRMS at ACROSS source room, the NRMS of source itself is small (< 2%) and the environmental changes affect the NRMSs of the field stations showing very large variations. Because the field geophones were located at the surface and the test field has more than 64 water-pumping stations, the apparent NRMSs observed at the grid stations show great temporal variation, which are considered time lapse itself. In addition, the weakening of first-arrivals mentioned above could affect the NRMS variation.

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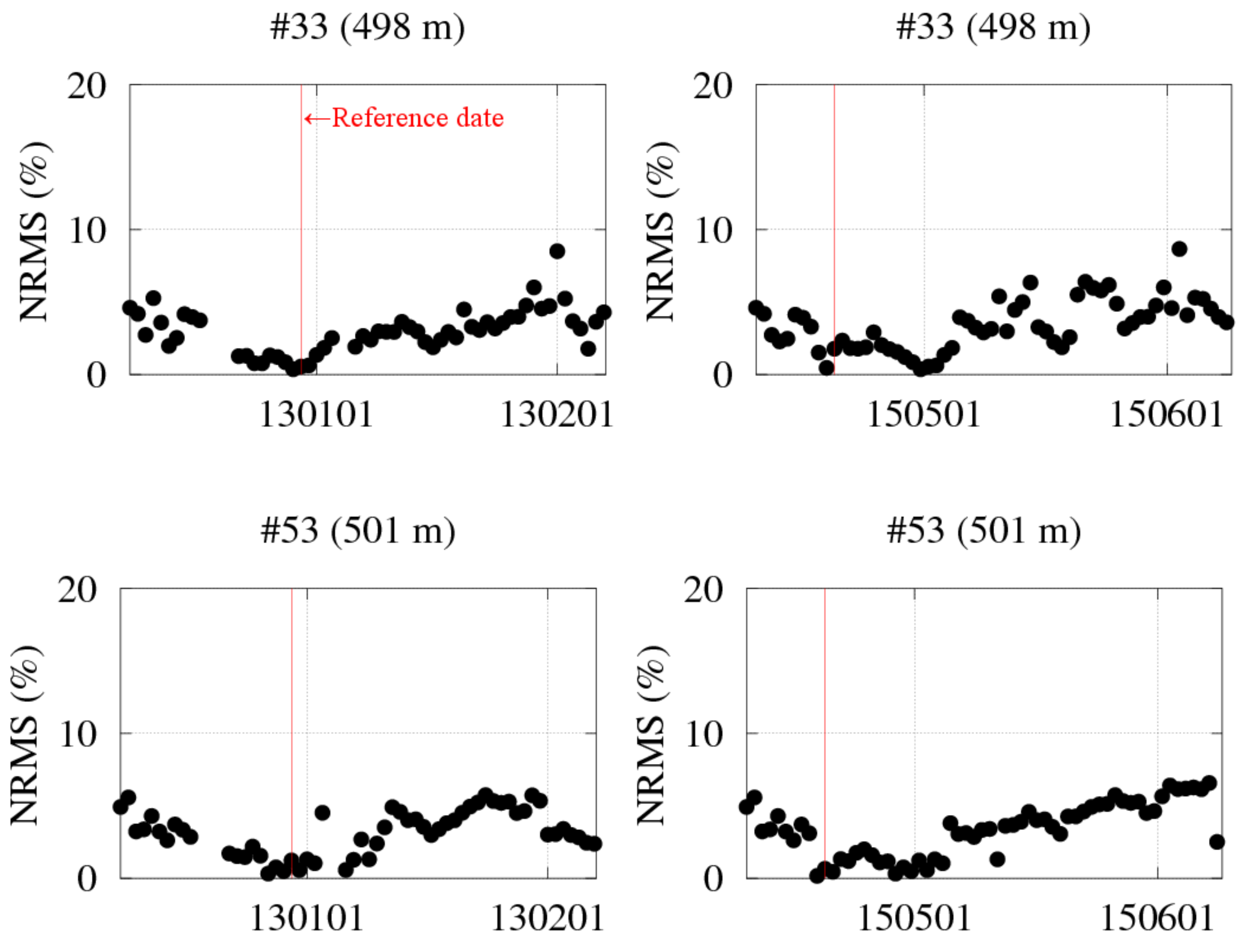
Keywords: Time lapse, Subsurface, CCS, repeatability, ACROSS



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