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AN INTEGRATED APPROACH TO ASSESSING SEISMIC SIMULATION BASED ON ANALYSIS OF PRESEISMIC, COSEISMIC, POSTSEISMIC AND INTERSEISMIC CREEP, AND CREEP DAMAGE EVOLUTION

Теоретичні та чисельні дослідження даної роботи направлено на дослідження Parkfield землетрусів. Головні дослідження направлено на пояснення впливу фізичної та хімічної дифузії, деформацій повзучості в досейсмічному, сейсмічному, післясейсмічному та міжсейсмічному періодах, включаючи сталу стадію повзучості, дифузійної повзучості, циклічної та динамічної повзучості, великих деформацій, асиметрії повзучості при розтягу та стисканні, явища ділатансії, активного та пасивного розвитку пошкоджуваності, циклічних варіацій крайових умов, історії тектонічних навантажень, сейсмічної активності земної кори на формування розломів та розривів кори та відповідно на виникнення катастрофічних випадків. Основні дослідження сфокусовано на дослідженні того, як дифузія, досейсмічна, сейсмічна, післясейсмічна та міжсейсмічна повзучість, великі деформації, розвиток процесів пошкоджуваності та заліковування, рух фронту руйнування, крайові умови можуть бути змодельовані для розуміння Parkfield землетрусів та прогнозування нових руйнівних землетрусів.

In this paper, a comprehensive theoretical, numerical and computational investigation based on the analysis of the Parkfield earthquakes will be carried out with the main focus directed at the understanding on how physical and chemical transport phenomena, creep deformation with preseismic, coseismic, postseismic and interseismic periods including steady-state static creep, diffusional creep, cyclic creep and dynamic creep, large strains, tension/compression creep asymmetry, creep dilatancy, active creep damage state (degradation) and passive creep damage state (healing), cyclic variations of velocities in boundary conditions, and tectonic loading history affect fault sliding, seismic activity in the crust surrounding a fault including accelerated seismic release characterized by cumulative Benioff strain, spatio-temporal seismicity patterns, large earthquake cycle on the fault as well as future destructive events. Furthermore, focus is put on how the diffusion, preseismic, coseismic, postseismic and interseismic creep processes, large strains, creep damage evolution including degradation and healing, movement of the front of creep rupture, boundary conditions as well as tectonic loading history may be modeled in order to understand the workings of the Parkfield earthquakes and to predict new destructive earthquakes within a much shorter time frame than currently possible.

Introduction. The specific objectives of our international cooperation are:

- to identify the features of creep deformation and damage evolution with preseismic, coseismic, postseismic and interseismic periods,
- to develop an integrated three-dimensional micro-meso-macro constitutive framework at large strains based on the modeling of diffusional creep, cyclic creep, dynamic creep and creep damage evolution including degradation and healing in the seismogenic zone, and of steady-state static creep in the surrounding crust that will then be used to calculate the time dependent distribution of stresses, strains including cumulative Benioff strain, and creep damage along the San Andreas fault's flanks as well as to generate an earthquake cycle with distinct preseismic, coseismic, postseismic and interseismic periods, and foreshock-mainshock-aftershock sequences, and additionally to predict new destructive Parkfield earthquake within a much shorter time frame than currently possible,
- to establish a relation between transport phenomena, preseismic, coseismic, postseismic and interseismic creep processes at large strains, tension/compression creep asymmetry, creep dilatancy, creep damage evolution including degradation and healing in the seismogenic zone, movement of the front of creep rupture, cyclic variations of velocities in boundary conditions, tectonic loading history and evolution of stresses, strains including cumulative Benioff strain, and creep damage along the San Andreas fault's flanks, and fault sliding, spatio-temporal seismicity patterns, self-driven mode switching of earthquake activity on the fault, large earthquake cycle on the fault and foreshock-mainshock-aftershock sequences,
- to incorporate an integrated micro-meso-macro constitutive framework at large strains developed in this project as well as an integrated constitutive framework developed by Ben-Zion and Lyakhovsky (2006), into the ANSYS codes in a form of the computer-based structural modelling tools for analyzing the distributions of stresses and strains along the fault's flanks and in the surrounding crust over time, for analyzing the rock hardening, and creep damage evolution including damage-induced rock softening processes and healing under preseismic, coseismic, postseismic and interseismic creep conditions, for analyzing the movement of the front of creep rupture along the fault's flanks, and for new destructive California earthquakes predictions within a much shorter time frame than currently possible,
- to provide a comparison of the present model predictions based on the laboratory results of creep up to rupture and acoustic emission rock mechanics experiments over time under constant and cyclic loadings as well as on geophysical, geodetic and seismological data, with the results of the simulations based on the constitutive framework of Ben-Zion and Lyakhovsky (2006),

- to formulate general practical recommendations based on the results of computational modeling and seismic simulation for the 1857, 1881, 1901, 1922, 1934, 1966 and 2004 Parkfield earthquakes, on how to predict where and when a future, large earthquake may occur.

1. State of the art. A better understanding of the earthquake faulting and earthquake process with distinct preseismic, coseismic, postseismic and interseismic periods should enable scientists to develop seismic hazard assessment tools based upon improved estimates of the locations and sizes of future earthquakes and the time-dependent probabilities of their occurrence [1]. It will allow incorporation of realistic simulations of dynamic rupture and wave propagation into hazard models so that time histories of strong ground-shaking from scenario earthquakes needed in performance-based seismic design of structures can be synthesized. There are many approaches to such problems, including statistical physics, continuum mechanics, laboratory experiments, and field observations.

The statistical physics analyses provide powerful tools for studying possible types and statistical properties of event patterns. However, they cannot be used to calculate details of stress and displacement fields in a deforming solid [2].

The framework of subcritical crack growth was developed originally as an empirical description of laboratory observations involving primarily the evolution of a single crack from an early quasi-static deformation at small size scales to an unstable dynamic rupture at a critical length [2]. This may be referred to as a deterministic continuum mechanics approach at a relatively small single scale. It was established [2] that subcritical crack growth before a large dynamic failure on a fault does not provide a satisfactory explanation of accelerated seismic release characterized by cumulative Benioff strain.

Numerous seismological observations for small earthquakes [3-5] suggest consistently that fault structures governing seismic response tend to evolve with cumulative slip toward geometrical simplicity and the continuum-Euclidean framework at all scales. Initial deformation is associated with strain hardening (Stage A). At this stage there is creation of granularity and band-limited fractal structures at several hierarchies. After a relatively small initial strain there is localization to tabular primary slip zones accompanied by a transition to strain weakening (Stage B). At stage C large deformation is dominated by strain weakening and overall evolution at different scales toward Euclidean geometry and progressive geometrical simplicity and regularization. The initial complex structure becomes largely passive at this stage.

Numerical simulation of slip instabilities on a vertical strike-slip fault without damage evolution in a 3-D half-space has been performed for various models belonging to two different categories. The first category [6] is related to the consideration of realistic strike-slip fault zones (Fig. 1).

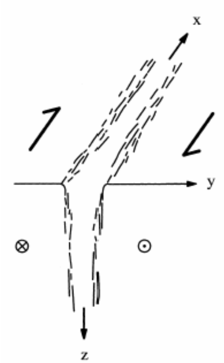

Fig.1. A schematic representation of an individual strike-slip fault system with a 3-D geometric disorder [6]

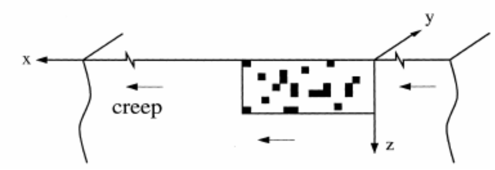

Fig.2. A simple representation of the 3-D disordered fault system by a 2-D fault embedded in a 3-D half-space [7]

The second category [7, 8] is much simpler modeling approach that contains a computational grid (Fig. 2) where evolving seismicity patterns are generated in response to ongoing loading imposed as slip boundary conditions on the other fault regions. The brittle properties of the computational grid are characterized by static strength threshold and arrest stress distributions that are spatially heterogeneous but fixed in time, and a dynamic weakening coefficient. The latter simulates a reduction from static friction to dynamic strength at a point on a fault sustaining multiple slip episodes during a given model earthquake. The other fault regions are under conditions of creep with constant velocity.

2. Modeling of earthquake process and earthquake faulting. In order to reproduce coupled evolution of earthquakes and faults it is necessary to introduce in a model the structural evolution toward increasing localization and simplicity as an expected outcome for deformation in a medium governed by any strain weakening rheology. In this regard, Lyakhovsky et al. presented in [9] a formulation of a lithospheric model consisting of a seismogenic zone governed by nonlinear elastic damage variable over a viscoelastic half space. The employed damage rheology is a generalization of Hookean elasticity to a nonlinear continuum mechanics framework accounting for large strain and irreversible deformation. The evolving damage in the seismogenic layer simulates the creation and healing of fault systems as a function of the deformation history. The upper crust is coupled viscoelastically to the substrate where steady plate motion drives the deformation. A parameter space study for this model indicates [2, 10, 11] that the types of generated fault structures and earthquake statistics are governed by the ratio of the time scale for material healing (t_1) to the time scale for loading (t_2). In general, each brittle failure is associated locally with both strength degradation and stress drop. The value of t_1 depends on the rheology and it controls the time for strength recovering after the occurrence of a brittle event. The value of t_2 depends on the boundary conditions and large-scale parameters (which also determine the average time of a large earthquake cycle) and it controls the time for re-accumulation of stress at a failed location. Relatively high ratios of t_1/t_2 lead to the development of geometrically regular fault zones and frequency-size statistics of earthquakes compatible with the characteristic earthquake distribution. Relatively low ratios of t_1/t_2 lead to the development of highly disordered fault zones and frequency-size event statistics compatible with the Gutenberg-Richter distribution. Note that intermediate cases of t_1/t_2 produce a ‘‘mode-switching’’ behavior in which the fault zone structures and seismicity patterns alternate between time intervals associated with relatively regular structures and characteristic earthquake distribution and intervals associated with relatively disordered structures and the Gutenberg-Richter statistics. The results under discussion are compatible with the seismological observations [4, 5].

Thus, at present, a unified framework for earthquake process and earthquake faulting does not exist. Additionally, to the best of the authors' knowledge, the framework given above can be considered as the best framework for modeling crustal deformation related to the coupled evolution of earthquakes and faults.

A number of comments need to be made in reference to the framework described in [2, 9-11]. Firstly, the damage model in [2, 9-11] ignores gradual accumulation of irreversible creep strains. As an example, the creep curve of rocksalt [12] from triaxial compression test with constant differential stress and confining pressure is shown in Fig. 3. It is seen that the creep strain of rocksalt at the instant preceding rupture can reach value of 15%. Secondly, it was shown in [2] that the results following from the nonlinear elastic damage model under discussion are compatible with the cumulative Benioff strain associated with the accelerated seismic release. On the other hand, in 1951 year Benioff analyzed in [13] mechanisms of aftershock considering creep behavior. Finally, recently published in [14, 15] model is a further development of damage rheology framework given in [2, 9-11] for evolving effective elasticity. The final variant of the framework accounts for irreversible creep strains with consideration of the same damage variable. The open question here: is it possible to predict the creep curves of the material using the framework under discussion, the single scalar damage variable under consideration and model parameters found from the basic experiments given in [14, 15]?

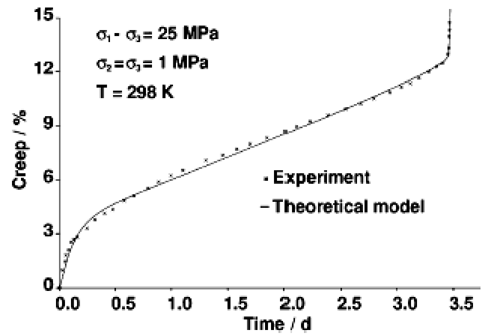

Fig.3. Creep curve of rocksalt [12]

We now return to the original questions of Rice formulated in [1]: (1) Why is the stress level low (<200 bars) along high-slip plate-bounding faults where the large earthquakes occur but high (consistent with lab friction) in the more stable crust where large earthquakes rarely occur? (2) Is the rheology at the base of the seismogenic zone controlled by hot frictional sliding on the fault plane, which satisfies RSD friction and exhibits velocity strengthening, or by a high-temperature creep mechanism? (3) Does dilatancy or strong velocity strengthening stabilize shallow fault rupture?

The answer to the first question of Rice can be found in the nature of the creep behavior of the seismogenic layer associated with the fast stress relaxation. The second question of Rice has been analyzed in [16] using the framework given in [14, 15]. It was found the closed relation between the creep damage model, and rate- and state-dependent friction. Thus, introduction of hot frictional sliding on the fault plane and consideration of creep deformation are different (but equivalent) ways to model the earthquake process. In the same way, dilatancy and strong velocity strengthening should be considered as different (but equivalent) ways to stabilize shallow fault rupture. Active damage state with open microcracks (Fig.4, a) in rocks is realized under compression with zero pressure while the passive damage state with closed microcracks (Fig.4, b) occurs under compression with nonzero confining pressure. Therefore, in order to describe the processes of degradation and healing in the seismogenic zone it is necessary to introduce the first invariant of the stress tensor into the creep model as well as creep damage model.

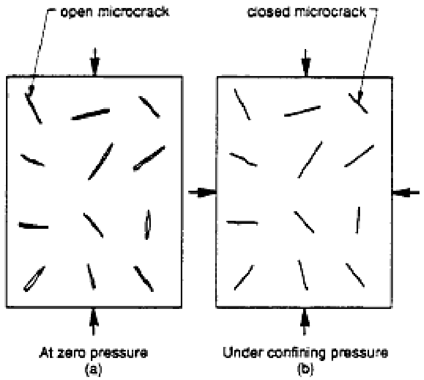

Fig.4. Degradation (a) and healing (b) in rocks

The modeling of creep in the seismogenic zone and surrounding crust is a nonlinear problem, and the adequate simulation of creep processes involves several difficulties. In order to overcome them, numerical methods involving three simulation steps which are all equally important have been used: accurate simulation of the kinematic (possibly nonlinear) and the quasi-static behavior; appropriate constitutive simulation of the rheological properties of the material; mechanical representation of the creep process including transport phenomena and creep damage. Each category of simulation directly influences the overall mechanical relevance of the results. Various attempts to include these effects in the analysis have been made, but due to the complexity of the creep problem, most investigators have concentrated their efforts on one specific aspect. Special numerical techniques for solving creep nonlinear equations have to incorporate mixed schemes of discretization in space and time.

3. New conception. The aim of the present paper is the presentation of a suitable strategy which enables us to analyze creep deformation, creep damage evolution and movement of the front of creep rupture in the seismogenic zone with preseismic, coseismic, postseismic and interseismic periods as well as steady-state static creep in the surrounding crust. Total strains are composed of a nonlinear elastic part without damage, thermal part and a part due to creep related to a con-

tinuum damage parameter by Kachanov-Rabotnov.

Let us consider the features of creep in the seismogenic layer.

Firstly, let us consider the coupling of creep with different physical and chemical transport phenomena. For example, the chemical influence of water leads to creep deformation and failure through such mechanisms as „stress corrosion cracking" that can allow rocks to fail over extended periods of time at stresses far below their short-term failure strength and at low strain rates. Another case of the diffusion process is the stress-accelerated oxygen diffusion into the bulk of a rock and formation of brittle oxides along the grain boundaries. The diffusion of oxygen can be described by the second Fick's law [17]:

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right)$$

where variable C is the oxygen concentration, and D is the diffusivity parameter. The diffusion process introduces an important time scale into the constitutive model. When a material is uniformly oxidized in an environment with a constant oxygen concentration, oxide production can be described by an empirical oxidation law, which relates the amount of oxide produced, $P(t)$, to oxygen concentration C and exposure time t. For example, the Logarithmic Reaction Law with three oxidation parameters that may depend on C is given by

$$P(t) = k \log(\alpha t + \beta) .$$

The rate of oxidation, $R_0(t)$, is then determined by differentiating $P(t)$ with respect to time while holding the oxidation parameters constant. If these parameters depend on C, and C varies with time (e.g. due to oxygen diffusion), then the rate of oxidation must be determined based on the Boltzmann superposition principle. For example, suppose in (2) that only k depends on C, then the rate of oxidation can be shown to be

$$R(t) = R_0(t)H(t) + \int_0^t \frac{\partial R_0}{\partial k}\frac{\partial k}{\partial C}\frac{\partial C}{\partial \tau} H(t-\tau)d\tau .$$

It should be introduced into the diffusional creep model and creep damage model in accordance with recommendation given in [18]. Here $H(t)$ is the Heaviside function. The oxidation law introduces another important time scale into the constitutive model. Modeling of creep and creep damage with consideration of tension/compression creep asymmetry, creep dilatancy, effect of hydrostatic pressure and active/passive creep damage state has been earlier performed for different materials in [19- 21].

Secondly, the creep law and damage evolution equation for specimens loaded by fixed and cyclic loads have been established by the set of experiments [22, 23]. The arbitrary functions in the constitutive and evolutions equations have been established from experiment too. It is well known from experiments [22, 23], that if the character of loading is harmonic in time with a small period and with cyclic load component smaller than the static load the global creep process of the material is not just a repeated „microcreep" process . The influence of the varying stress part in each cycle on the creep process rate and on the life-time is a physical phenomenon, which is referred to as dynamic creep. By neglecting inertial forces, this phenomenon will be referred to as cyclic creep.

Let us consider dynamic (or cyclic) creep and dynamic (or cyclic) creep damage evolution in the seismogenic zone coupled with the surrounding crust and subjected to fixed and cyclic loads. Creep analysis, using a class of implicit single step algorithms, is not possible, because the large number of small time steps usually required for accurate solution could not be successfully extended to dynamic creep problems. This consideration implies a large consumption of computer time. Therefore it is quite interesting to seek solutions by other methods. For example, use of two time scales method enables us to handle two approaches to models for evaluating the stress-strain state under creep conditions [22]. In the first approach „fast time" models give an adequate mathematical description of the behaviour of an elastic body under fast cyclic loading. In the second one, the „slow time" model gives the mathematical description of the creeping body as well as damage evolution under fixed loading. On the other hand, this model takes into account the distribution of amplitudes of the effective stress corresponding to results previously obtained on the basis of the second approach. The mathematical technique of the theory of two time scales leads to some „homogenization" of the creep process. Generally speaking, homogenisation is the approach for simulating global homogeneous creep behaviour with local inhomogeneities periodically growing in time. If the character of loading is time-harmonic with a small period and with amplitude smaller than the fixed load, it is well known from experimental investigations that the global creep process of a material does not depend on repeated „micro-creep" process. Creep analysis using a class of explicit or implicit single step algorithms is usually required for accurate solution. Modern software, for example, ANSYS capable of handling all of the above-mentioned effects are in use now.

A comparison of the present model predictions with the results of the previous simulations of Ben-Zion and Lyakhovsky in [15], and computational modeling and seismic simulation for the 1857, 1881, 1901, 1922, 1934, 1966 and 2004 Parkfield earthquakes will be the main target in the future research. The basis for a successful completion of this research is definitely given since the participating researchers from Kharkov and Kansas City have an invaluable experience, accumulated over the past several years, in the computational modeling and simulation of different nonlinear physical phenomena.

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