A Hybrid Technique to Compute the Pore Pressure Changes Due to Time Varying Loads: Application to the Impounding of the Itoiz Reservoir, Northern Spain

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ABSTRACT

In the low frequency limit of the Biot equations the variations of the pore pressure in a fluid saturated elastic medium can be approximately described by a Homogeneous Diffusion Equation (HDE). It can be used, for example, to reconstruct the tensor of hydraulic diffusivity when connecting the microseismicity associated with fluid injection in boreholes, and assuming that these injections cause perturbations of the pore pressure in the rock. In poroelasticity this can be considered as an uncoupled problem. That is, elastic stresses and pore pressure are independent of each other in the governing partial differential equations of the problem. On the other side, those phenomena in which it is necessary to take into account the systematic influence of elastic stresses and pore pressure on each other are known as coupled problems. The intermediate problem, in which pore pressure does not influence the elastic stresses whereas the stresses influence the pressure, is known as the decoupled one. This approximation leads to an Inhomogeneous Diffusion Equation (IDE) that is being commonly used to analyse the pore pressure variations next to dams due to time varying water loads in their reservoirs. When considering flow boundary conditions, the solution of this equation can be obtained as the superposition of a term computed from the HDE with the Dirichlet boundary condition (the term due to the pore pressure diffusion), and the solution of an initial value problem in which the inhomogeneous term related with the stress variations in the IDE is considered (the solution due to the compression in the media). In this work we use a hybrid technique to estimate the pore pressure changes in this decoupled problem in which two different techniques are joined to calculate each one of the partial solutions. This hybrid technique has been used to estimate the pore pressure variations produced by the impounding of the Itoiz reservoir, northern Spain. The filling of this reservoir began in January 2004 and every hydrological year received water reaching in 2008 its maximum capacity with approximately 90 m of water column at the dam. We give special attention to the pore pressure variations at the hypocenter locations of the main earthquakes of the series occurred on September 2004 next to Itoiz reservoir, with magnitudes $M \leq 4.6$.

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INTRODUCTION

The equations of dynamic poroelasticity ([1]) predict the existence of two compressional and one shear wave in the system. The first compressional wave corresponds with the elastic P wave, and the second compressional with the diffusion-wave for frequencies lower than the critical Biot frequency. The shear wave is the seismic S elastic wave propagating in the medium. Roeloffs [2] defined three types of approximation for the solution of the equations corresponding to the quasi-static poroelasticity, which can be used to study the second P diffusive wave: the uncoupled, in which elastic stresses and pore pressure are independent of each other in the governing partial differential equations of the problem; the coupled, where the elastic stresses influence pore pressure and vice versa; and the decoupled, in which pore pressure does not influence the elastic stresses whereas the stresses influence actively the pore pressure. The decoupled approximation is commonly used to analyse the pore pressure variations next to dams due to time varying water loads in their reservoirs. The solution of the differential equations which govern this problem can be expressed by the sum of two partial solutions: the term due to the boundary conditions of the problem (p_{BC}), and that corresponding to the initial conditions of the pore pressure in the medium (p_{IC}).

Here we use a hybrid technique to estimate the pore pressure changes in the decoupled problem in which two different techniques are joined to calculate each one of the solutions. The term due to the pore pressure diffusion is obtained using the Green functions of the problem, whereas the second term due to stress time changes is computed with a Finite Difference Method (FDM). This hybrid technique has been compared with a previous published methodology, and subsequently has been used to estimate the pore pressure variations produced by the impounding of the Itoiz reservoir, northern Spain.

THE HYBRID METHOD

When considering the quasi-static poroelastic theory (see e.g. [3]) in the 3D decoupled approximation, it can be shown that the behaviour of the pore pressure variation in time and space follows the IDE:

$$c\,\Delta p = \frac{\partial}{\partial t}\left(p - \frac{B}{3}\theta\right) \qquad (1)$$

where Δ is the Laplace operator, $\theta = \tau_{xx} + \tau_{yy} + \tau_{zz}$, ($\tau_{ij}$ the elastic stress tensor), B is the Skempton's coefficient, and c the hydraulic diffusivity.

The solution for the pore pressure variation at equation (1) can be expressed by the sum of two partial solutions (see [4]) as

$$p = p_{BC} + p_{IC} \qquad (2)$$

where p_{BC} refers to the term due to the boundary conditions and p_{IC} to the initial condition of the pore pressure in the medium. In water reservoirs and with the Dirichlet boundary condition the pore pressure p_{BC} diffuses from the free surface to the poro-elastic media to reach the equilibrium situation. This term is no influenced by the compression induced by the water loads. In fact, [4] proposed the calculation of this pore pressure by means of Green's function based on diffusion solution ([5]) in the HDE:

$$c\,\Delta p-\frac{\partial p}{\partial t}=0 \tag{3}$$

On the other hand, the partial solution of the initial condition problem is the one that takes into account the stress variations in the IDE eq. (1). The changes in the compression in the media due to the varying water loads at $z = 0$ induce instantaneously pore pressure variations that subsequently diffuse as well.

If $P(x,y,t)$ are the stresses on the surface $z = 0$ of the poro-elastic media produced by the water loads for $t > 0$, the solution for p_{BC} for the flow boundary condition problem (Carslaw and Jaeger, 1959) can be expressed as

$$p_{BC}(x,y,x,t)=c\int_{0}^{t}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}P(x',y',\tau)\left.\frac{\partial G(x,y,z,t;x',y',z',\tau)}{\partial z'}\right|_{z'=0}d\tau\,dx'dy' \tag{4}$$

where $G(x,y,z,t;x',y',z',\tau)$ is the Green's function of the problem $G(x,y,z,t;x',y',z',\tau)$, that is, the pore-pressure at time t at (x,y,z) due to a unit instantaneous point source at (x',y',z'). Thus, once $P(x,y,z,t)$ is known, Eq. (4) can be solved numerically to calculate the p_{BC} solution. For a specific problem, the distribution of loads can be irregular depending on the geometry of the water reservoir, making that the spatial integrals should be solved with an appropriate discretization. On the other hand, the information about the evolution in time of the surface loads in the reservoir usually can be obtained in a set of time intervals, showing from a time to the following one, three possibilities in the load: i) no change, ii) increase, or iii) decrease. To consider appropriately these possibilities, we follow the following procedure: we first divide in a set of time intervals the time integral in eq. (4), after the integral of each one of the intervals is calculated analytically considering a linear function for the load, and taking into account its corresponding change or not change.

In order to calculate the p_{IC} of eq (2) an explicit Finite Difference Method (FDM) is employed. We consider a rectangular grid with steps Δx, Δy and Δz (see Figure 1), and time step Δt. Using this discretization, the approximation for the spatial partial derivatives, which appear in eq (1) is expressed using a fourth order $O(\Delta x)^4$ finite difference scheme. Thus for a homogeneous media, the derivatives in the coordinates x, for a given time $t = m\,\Delta t$ (m a natural number), are expressed as

$$\left(c\frac{\partial^2 p}{\partial x^2}\right)^m_{i,j,k}\approx c_{ijk}\frac{-p^m(i+2,j,k)+16p^m(i+1,j,k)-30p^m(i,j,k)+16p^m(i-1,j,k)-p^m(i-2,j,k)}{12(\Delta x)^2} \tag{5}$$

where the subscripts i, j and k correspond to the spatial position (i to x, j to y and k to z), and the superscript m to the time position. Time derivatives in equation (1) are computed with a first order scheme. The term where appears the variations of stresses (θ) can be computed, when the time varying loads are known, by solving the Boussinesq problem for the surface water loads step by step in time.

RESULTS FOR THE ITOIZ RESERVOIR (NORTHERN SPAIN)

The Itoiz reservoir located in Navarra, northern Spain (Figure 1), is a newly constructed gravity dam that stores the water flows of the Irati and the Urrobi rivers. The dam has a total height of 121.0 m and a total length of 525 m. Eight months after the beginning of its impoundment a clustered seismic series, located between the city of Pamplona and the Itoiz lake, began on September 18, 2004 ([6]). The series was headed by an Mw = 4.7 mainshock, followed by several moderate and small aftershocks. The mainshock and the largest aftershock were widely felt in this region. Different works have been published in relation with the seismic characteristics of the series and the possible relation of seismicity with the water level change of the lake (e.g. [6]).

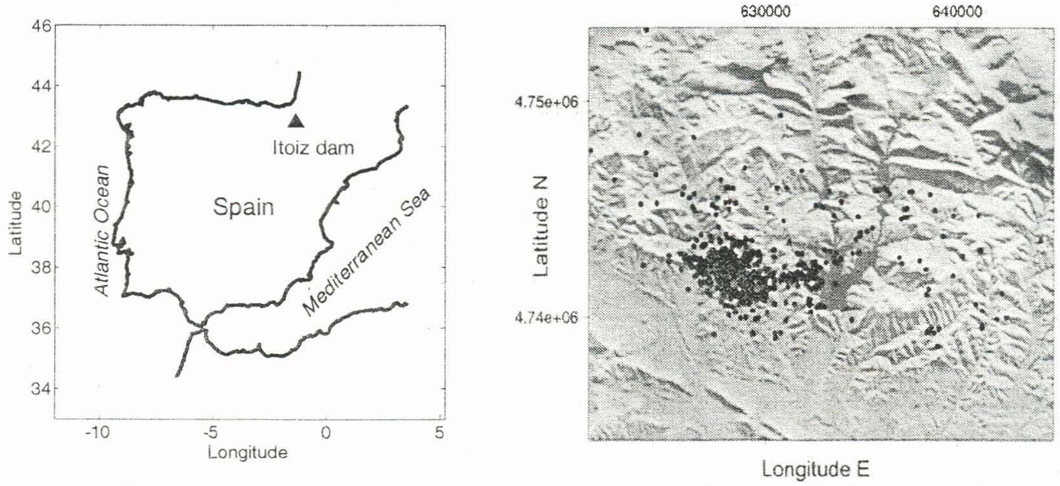

Figure 1. Location map, general seismicity, and relative location to Itoiz reservoir of the 2004 seismic series. The mainshock and largest aftershock earthquakes are shown with red circles. Aftershock locations for the interval between September 22 and October 20, 2004, are shown in brown circles while blue circles show aftershocks between April 14 and October 8, 2005.

Here we study the effects of the surface water loads on the subsurface state of pore pressure and its possible relation with seismicity, near the Itoiz reservoir. We use the time histories of the lake levels (THLL) and the Digital Elevation Model (DEM) of the zone. Subsurface stress changes, to compute $\Delta\theta/\Delta t$ for the p_{IC} solution, due to the water loads are computed by means of the Boussinesq solution for a homogeneous elastic halfspace.

In Figure 2 we show the evolution of the water level and of the total pore pressure change p, with the partial solutions corresponding to the compressive p_{IC} and the diffusive p_{BC} parts, due to the surface water loads during one year from the beginning of the impounding in January 2004. Here we assumed a hydraulic diffusivity of c = 1.0 m^2/s, a Skempton coefficient of $B = 1$ and a Poisson coefficient equal to 0.25.

In Figure 3 we show the snapshots of the p_{IC} solution at a depth of 6 km, every month from the beginning of the impounding. This component of pore pressure is associated with the rapid triggered-reservoir seismicity observed at various water reservoirs ([7]). In contrast, the delayed response of a reservoir, is dependent on the diffusion of water and pore pressure from the reservoir to the hypocentral zone, and is related with the partial diffusive term of the pore pressure p_{BC}. Note that in our computations the time of occurrence of the mainshock (September 2004) corresponds to day 243, in which the $p_{IC} \approx 250$ Pa at the hypocenter.

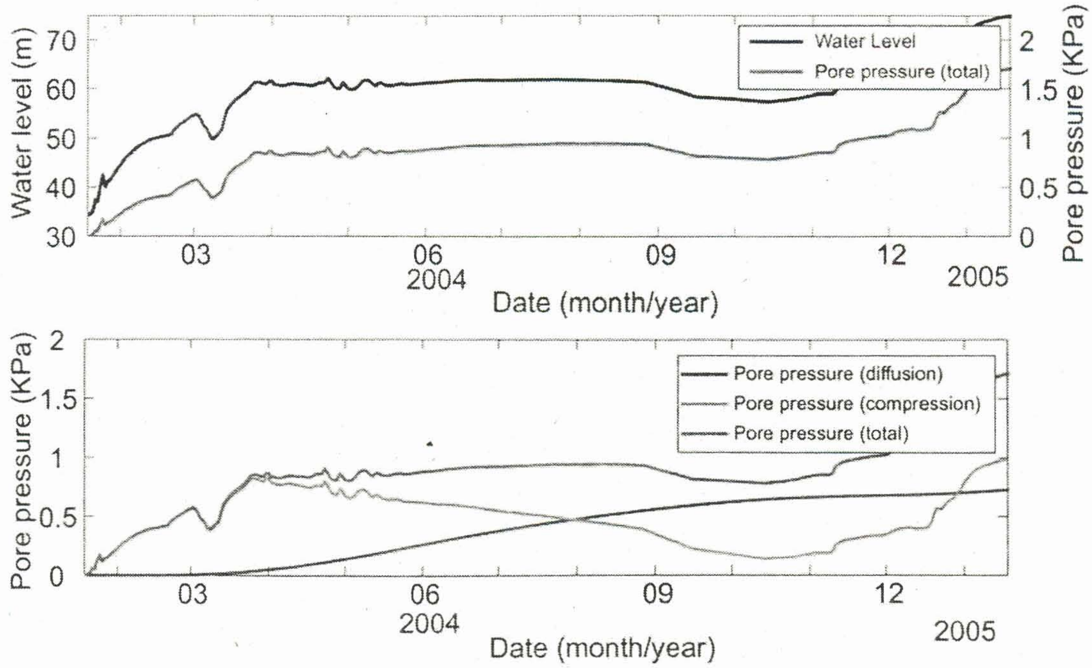

Figure 2. up) Temporal evolution, from the beginning of the impoundment, of the total pore pressure change (in red) and of the water level (in black) at the mainshock hypocenter. down) Temporal evolution of the total pore pressure change (in red) and partial solutions p_{IC} (in green) and p_{BC} (in blue).

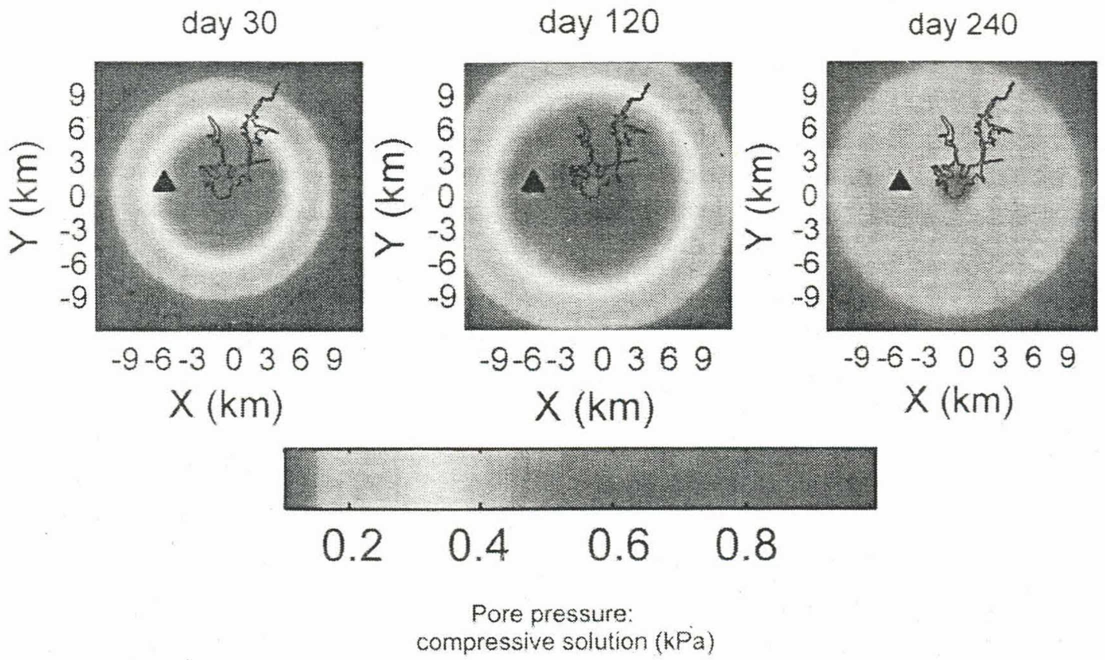

Figure 3. Snapshot views at different days from the beginning of the impoundments of Itoiz dam for the compressional component p_{IC} computed at a depth of 6 km

DISCUSSION AND CONCLUSIONS

The temporal pore pressure variations due to the impounding of the Itoiz reservoir, in the western Pyrenees (northern Spain) have been computed using a hybrid numerical technique. At the time of occurrence of the mainshock in the september 2004 seismic series the pore pressure change was of about 1000 Pa at the hypocenter, whereas the compressive partial solution was $p_{IC} \approx 250$ Pa. This shows that, in case of reservoir-triggered seismicity at Itoiz dam, its not due only to a rapid response produced by this compressive term, but to the combination of this term together with the diffusion of water and pore pressure from the reservoir to the hypocenter, that is, with the p_{BC} solution. However, other question is appearing when analyzing our results. As shown in Fig. 3, at other early times and at other different positions of the occurrence of the mainshock, the pore pressure p_{IC} arrives to values of 1000 Pa. At these points, and when adding the diffusion term, their total pressures are greater than that at the mainshock hypocenter at the time of rupture. Why these locations did not failure, producing other earlier earthquakes?. The question is open, but one possible answer is that there was a pre-existent fault in the hypocenter with more aptitude to fail. This, together with the assumption of regional pre-existing stress field, as the produced by the Pyrenees geological range, and the pore pressure perturbation could be the origin of the September 18, 2004 earthquake.

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