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STOCHASTIC ANALYSIS OF THE VENICE UPLIFT DUE TO SEAWATER INJECTION INTO DEEP AQUIFERS

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Summary. In recent years, a project of anthropogenic Venice uplift by seawater injection into a deep brackish aquifer underlying the lagoon has been advanced. A major concern is the possible generation of differential vertical displacements at the ground surface, which should not exceed prescribed regulatory thresholds to guarantee the structural preservation of historical buildings. In this work, we analyze the effects that spatially heterogeneous hydraulic conductivity distributions in the injected formations may have on the uniformity of the induced land uplift.

1 INTRODUCTION

Worldwide, field evidence based on satellite measurements shows that injecting fluid underground may cause the land to rise. Anthropogenic uplift records of the order of tens of centimeters have been observed in several locations around the world. A comprehensive survey of cases where land uplift has been observed as a byproduct of fluid (water, gas, vapor) injection in geological formations may be found in Teatini et al[1].

In recent years, a project of uplift of the city of Venice, Italy, (Figure 1a) has been advanced as a measure to reduce the intensity and the frequency of *acqua alta* events. Coupled hydrologic-geomechanical finite-element (FE) simulations indicate that injecting 18 Mm^3/year over 12 disposal wells into a 600-850 m deep brackish aquifer may induce a land uplift of 25-30 cm in a 10-year period[2,3]. With this uplift, only 14 out of the 228 floods that occurred in Venice from 1870 to 2009 would have been higher than 110 cm, i.e. the nominal starting point of *acqua alta* events and the threshold for the activation of MOSE, the systems of mobile barriers currently under construction to protect the city from flooding.

While the geo-mechanical properties of the Northern Adriatic sedimentary formations proposed for seawater injection are well characterized from an extensive dataset obtained from radioactive marker measurements[4], permeability data are very scarce and sparse throughout the area of interest. In the simulations by Comerlati et al[2,3] uniform horizontal hydraulic conductivity, K, distributions with values ranging between 5×10^{-7} and 5×10^{-6} m/s were considered, based upon the results of some permeability tests conducted in the basin[5,6]. Vertical permeabilities were assumed to be one order of magnitude smaller. An important finding of Comerlati et al[2,3] was that the uplift distribution would be very uniform, with negligible displacement gradients throughout the city of Venice.

However, it is well know that hydraulic conductivity distributions in geologic formations are inherently heterogeneous and vary according to the scale of the medium affected by groundwater flow[7]. Therefore, a question arises as to whether a heterogeneous K field could produce non uniform uplift distributions and generate displacement gradients large enough to potentially damage Venetian monuments and palaces.

The major goal of this work is to address the issue of heterogeneity of the hydraulic conductivity distribution and evaluate the effects that this may cause on land uplift. This is carried out through a stochastic (Monte Carlo) simulation of land uplift where the heterogeneous hydraulic conductivity distribution is modeled using an ensemble of realizations of a spatially-correlated stationary random process characterized by a bivariate log-normal distribution with an exponential covariance model.

The analysis is performed on a three-well pilot project[8] designed to test the feasibility of the full scale injection plan. Since the horizontal scale of influence of the pilot project (Figure 1a) is of the order of 10 km and the injected formation has an average thickness of 250 m [2,3], a representative support scale for K is likely to fall between these two values. It is therefore assumed that the K heterogeneity occurs on a characteristic length of several hundred meters, closely related to the correlation scale assumed in the covariance model[9].

The uncertainty on the geostatistical parameters of the K field is addressed with a sensitivity analysis, where both the log-normal variance, σ^2, and the correlation length, λ, are varied over plausible ranges consistent with the sedimentary nature of the geologic basin and the space-time scale of the experiment. The median of the hydraulic conductivity distribution is assigned a value of 1.2×10^{-6} m/s, which is equal to the average K assumed in the deterministic simulations by Comerlati et al[3].

In each Monte Carlo simulation, an ensemble of K fields is used in groundwater flow simulations performed using a FE discretization of the injected aquifer system. The resulting realizations of pore pressure distribution are then implemented into a FE geomechanical model, which produces an ensemble of ground surface uplift fields, u_z. The cumulative distribution function (CDF) of the land uplift and its horizontal gradient, ρ_z, are then computed and used to evaluate the probabilities for u_z and ρ_z to exceed significant reference threshold values. Particular

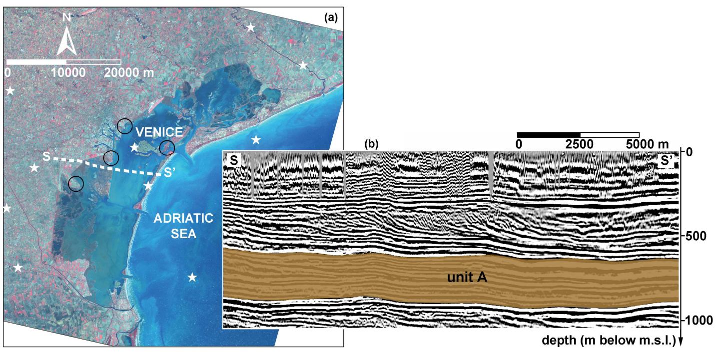

Figure 1. (a) Satellite image of the Venice Lagoon. (b) Seismic section of the Plio-Pleistocene subsurface with the aquifer Unit A proposed for seawater injection.

attention is given to the K scenarios that produce the largest gradient, which represents a potential risk to the preservation of the Venice architectural patrimony.

2 HYDROGEOLOGICAL SETTING AND MODEL SET-UP

2.1 Site description

The Venice lagoon is part of the north-eastern portion of the Po River plain (Figure 1a). The sedimentary infill mainly consists of a thick sequence of Messinian-to-Pleistocene turbidite deposits characterized by a basin-scale tabular geometry with thickness varying from several tens to hundreds of meters[10,11]. These sedimentary systems are almost entirely composed of thick-bedded sand/sandstone facies, which grade downcurrent into basin plain deposits of mud/mudstones with thin-bedded fine-grained sands/sandstones. Figure 1b shows a seismic cross section of the sedimentary basin where Unit A, the formation proposed for the implementation of the pilot injection project, is highlighted. This formation was deposited from Late Pliocene to Middle Pleistocene[12,13] and extends horizontally for about 300 km along the North-West–South-East–direction, and 100 km along the South-West–North-East direction[11]. Available data[10-12] indicate that Unit A has a rather regular and tabular behavior with a reduced lateral variability of the hydrologic properties.

2.2 FE model

The deformation of a saturated porous medium induced by water injection relies on the classical poro-elasticity equations[14]. Since in the aquifers of the Po River basin coupling between the flow and stress fields is weak for the timescales of practical interest[15], the poro-elasticity equations are solved using an explicitly coupled approach:

$$
\begin{aligned}
&(a) \qquad \nabla(\mathbf{K}\cdot\nabla p) = S_s \cdot \frac{\partial p}{\partial t} + q \\
&(b) \qquad \nabla\,\boldsymbol{\sigma} = \alpha\cdot\nabla p + \mathbf{b} \\
&(c) \qquad \boldsymbol{\sigma} = \frac{1}{(1-\nu)\cdot c_M(\boldsymbol{\sigma})}\cdot\left[(1-2\nu)\cdot\boldsymbol{\varepsilon} + \nu\cdot \mathrm{trace}(\boldsymbol{\varepsilon})\cdot\mathbf{I}\right]
\end{aligned}
\qquad (1)
$$

Equation (1a) represents the classical saturated groundwater flow equation, where: ∇ is the gradient operator, p is the fluid pressure, **K** is the hydraulic conductivity tensor, **q** represents prescribed source/sink terms; and S_s is the specific elastic storage. Equation (1b) governs the equilibrium of a porous medium undergoing a pressure gradient ∇p with $\boldsymbol{\sigma}$ the effective stress tensor, α the so-called Biot coefficient, and **b** the vector of applied forces. Equation (1c) is the non-linear hysteretic constitutive law that relates $\boldsymbol{\sigma}$ to the strain tensor $\boldsymbol{\varepsilon}$. **I** is the identity tensor; c_M is the vertical uniaxial compressibility, which varies with $\boldsymbol{\sigma}$ as shown in Comerlati et al[3]; and ν is the Poisson ratio, which is set to 0.3 [6]. The system of equations (1) is solved by FE, with the flow field computed first at each time step (Equation 1a), and stress and deformation then calculated using the pore pressure gradient as a strength source (Equations 1b and 1c). Since S_s is a function of c_M [16], the stress field is used to update S_s through c_M after each time step.

Figure 2 shows the main features of the high-resolution 3D FE grid generated using lithostratigraphic data of the Venice subsurface[8]. The model domain has a horizontal extent of 20×20 km, is centered at the location of the three injection well pilot plant, and is confined on top by the ground surface and on bottom by a rigid 10-km deep basement.

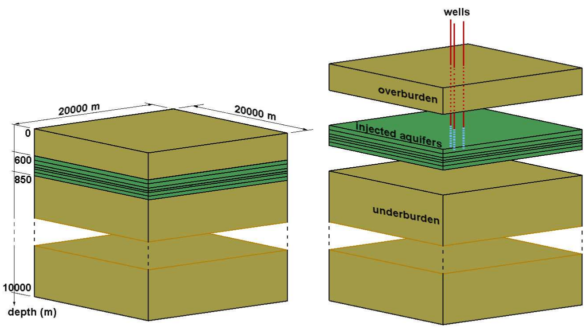

Figure 2. (a) Axonometric view of the 3D geomechanical grid and (b) horizontal view of the 2D groundwater flow mesh.

Similar to the deterministic simulations of seawater injection by Comerlati et al[3] and Castelletto et al[8], Unit A is discretized into six hydraulically disconnected subunits, whose thicknesses are shown in Figure 2. The compressibility in expansion is assumed to be 3.5 times less than in compression[4]. Hydrostatic pressure is assumed as initial condition and at the outer boundaries, located far enough from the injection area so as to be unaffected by flow and deformation over the simulated period. Zero flux on the basement is prescribed in the flow model, whereas standard Dirichlet conditions with fixed outer and bottom boundaries are imposed in the geomechanical model. A detailed description of these and other relevant data is provided by Castelletto et al[8].

The injection is performed through three wells located on the vertices of a 1-km side equilateral triangle for a 3-year time[8]. A constant 1.2×10^{-2} m^3/s flow rate is prescribed at each well and distributed through the six formations proportionally to the trasmissivity around the wells. In order to avoid the generation of a fissuring tensile stress, a maximum admissible over-pressure of 25 bars (2.5×10^5 Pa) is prescribed at each well. As hydraulic fracturing is not expected to occur, realizations where the above limiting value is exceeded are excluded from the Monte Carlo analyses.

2.3 Hydraulic conductivity scenarios

A stochastic simulation (or Monte Carlo) approach is followed, where uncertainty is addressed by generating a large number, N_{MC}, of equally likely realizations of the hydraulic conductivity field (K_k ; k=1, 2,..., N_{MC}). In each of the six layers into which Unit A is partitioned, the heterogeneous K distribution is specified as a spatially-correlated second-order stationary random process, characterized by a bivariate normal distribution along with an exponential covariance model in a log-transformed space. The geostatistical model is characterized by the parameters μ and σ^2, that is, the mean and the variance of the log-K distribution, and the isotropic correlation length λ of the covariance model. The hydraulic conductivity is assumed to be vertically homogeneous within any injected layer. No vertical correlation for the hydraulic conductivities of the six layers is assumed. In this work, the generation of the K fields is carried out using the direct Fourier transform spectral algorithm presented in Robin et al[17].

To address the uncertainty on the geostatistical parameters of the injected formations, a sensitivity analysis using combinations of values of σ^2 equal to 0.2, 0.5 or 1, with values of λ equal to 20, 100 or 1,000 m is performed. The above variability ranges are consistent with the quiet sedimentary nature of the basin and the spatial scale of the experiment[7]. As for the mean μ of the log-K distribution, a value of -5.921 is assumed, which corresponds to the average K of 1.2×10^{-6} m/s used in the deterministic simulations by Castelletto et al[8]. Figure 3 shows three realizations of the K field generated with σ^2=1.0 and λ equal to (a) 20 m, (b) 100 m and (c) 1000 m. At the aquifer scale, the K pattern is strongly influenced by the correlation scale, so that the scale of heterogeneity appears to be wider for larger λ values (Figure 3a) than for smaller λ values (Figure 3c).

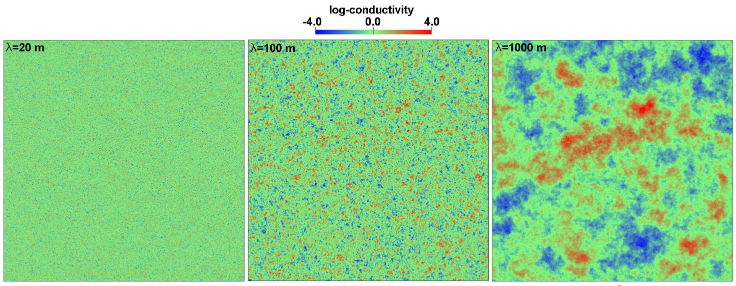

Figure 3. Example of K field generations obtained with σ^2=1.0 and λ values of 20, 100, and 1,000 m. Log-K values are scaled with respect to the median hydraulic conductivity.

3 RESULTS AND DISCUSSION

The ensembles of hydraulic conductivity fields generated for different combination of the geostatistical parameters, σ^2, and λ, are used in a series of Monte Carlo geomechanical simulations to produce corresponding ensembles of the surface uplift, u_z, distribution. In this study, a number N_{MC} =1,000 realizations is used. Such a large number is selected in order to: (i) delineate an accurate representation of the statistical distribution of the surface heave and its gradient ρ_z; and (ii) generate critical hydraulic conductivity scenarios in terms of an irregular surface deformation. Since the results of these stochastic simulations generally indicate that, as expected, the spread of the sampled statistical distribution increase with σ^2, only the results associated with the cases σ^2=1 are presented.

Figure 4a shows the profiles of the sampled CDF of the land uplift obtained for σ^2=1 and λ=20 m, 100 m and 1000 m; u_z is calculated at the center of the injection system, where the surface rebound reaches its maximum amplitude, and normalized with respect to its value as estimated in the deterministic homogeneous case (~5.5 cm). Each profile in Figure 4a is obtained by sorting the ensemble of u_z values in ascending order and calculating the CDF values as the ratio between the rank index and N_{MC}. The sampled CDF provides a direct estimate of the probability of the land uplift not to exceed any given value u_z. The CDF profile gives also a direct estimate on how parameter uncertainty reflects on the surface uplift. Similarly, Figure 4b shows the CDF profiles for the vertical gradient obtained for σ^2=1and λ=20 m, 100 m and 1000 m; ρ_z is calculated at a location in proximity to the two southernmost injection wells (Figure 5), where the gradient approaches its maximum, and is normalized with respect to the value estimated in the homogeneous case (~1.66×10^{-5}). Inspection of the profiles plotted in Figure 4 reveals that the spread of the statistical distributions of both u_z and ρ_z increase with the correlation scale λ. This effect can be traced

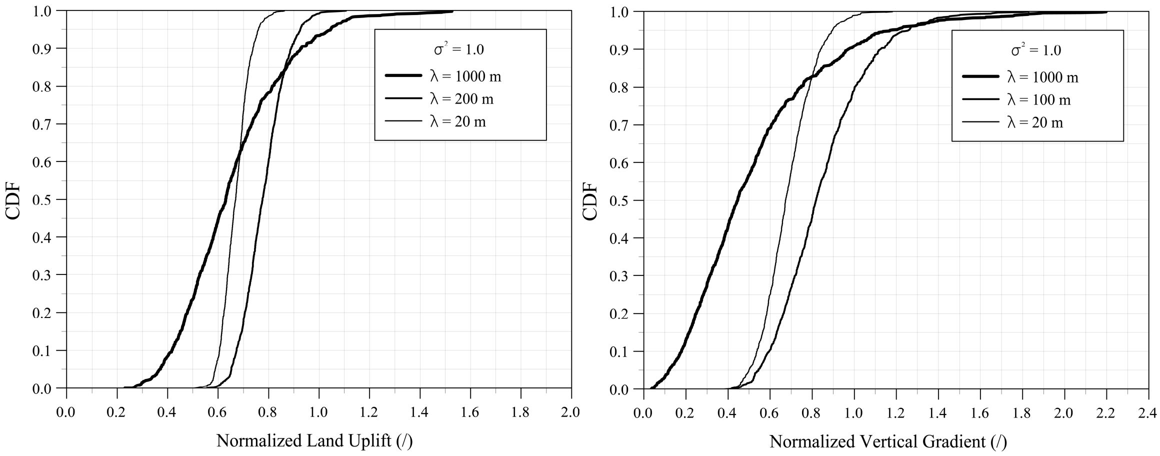

Figure 4. Sampled CDF profiles for (a) the land-uplift and (b) the vertical displacement gradient obtained for σ^2=1.0 and λ equal to 20 m, 100 m and 1000 m; u_z is calculated at a central location among the three injection wells and normalized with respect to its value as estimated in the homogeneous case (~5.5 cm); ρ_z is calculated at the location indicated in Figure 5 by a blue cross and normalized with respect to its value as estimated in the homogeneous case (~1.66×10^{-5}).

back to the wider heterogeneity of the K field observed at the regional scale for larger correlation lengths (Figure 3). In quantitative terms, it may be observed that, for λ =1000 m the 99th percentile of the normalized land uplift is about 1.6 (Figure 4a), whereas the same percentile is about 1 for λ =20 m. The profiles of Figure 4b show that the 99th percentile of the normalized uplift gradient increases from 1.28, for λ =20 m, to 2.2, for λ =1000 m. It is also interesting to observe that, the ρ_z median value (the 50th percentile) is significantly less (about 20-40 %) than the uplift gradient in the homogeneous case.

Figure 5 displays the contour maps of the uplift gradient ρ_z after 3 years, as predicted for the deterministic homogeneous case and in the heterogeneous cases for λ=20 m, 100 m, and 1000 m. In each heterogeneous case, the ρ_z field is calculated for the most pessimistic K scenario, that is, the one producing the largest uplift gradient in the ensemble. These maps indicate that the maximum ρ_z never exceeds three times the value obtained in the deterministic simulation. Figure 5 indicates that, in the most pessimistic case, the maximum ρ_z is about 4.5×10^{-5} and occurs for σ^2=1 and λ=1000 m. This value is: (i) about half the maximum differential displacement measured in Venice over the 1960's; (ii) 10 times smaller than the maximum limit allowed for masonry buildings (50×10^{-5}); and (iii) about 20 times smaller than the values currently being measured in some areas of Venice[18].

Figure 6 shows the results from a Monte Carlo simulation performed assuming σ^2=1, λ=1000 m, and K as vertically homogeneous within the entire Unit A thickness. This scenario can be viewed as an unphysical worst-case scenario. Figure 6 refers to the K realization that produces the largest ρ_z, and compares the heterogeneous case to the homogeneous case in terms of overpressure, aquifer expansion, and surface uplift induced by water injection.

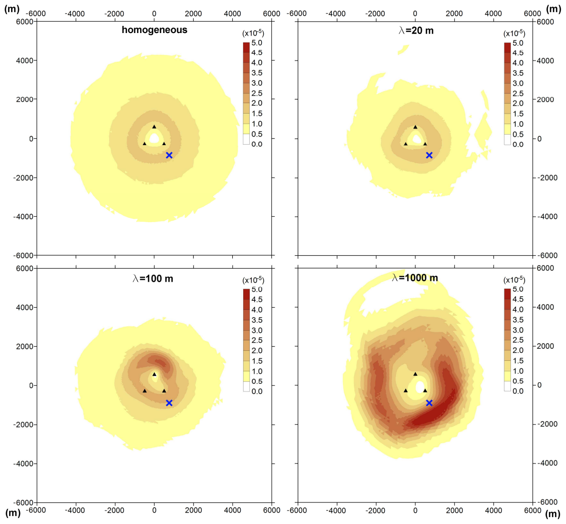

Figure 5. Differential vertical displacements after 3 years as obtained for the hydraulically homogeneous case and the realization that produces the maximum gradient of the ground vertical displacements with σ^2=1.0 and the three λ values used in the simulations. Injection wells are indicated by black triangles.

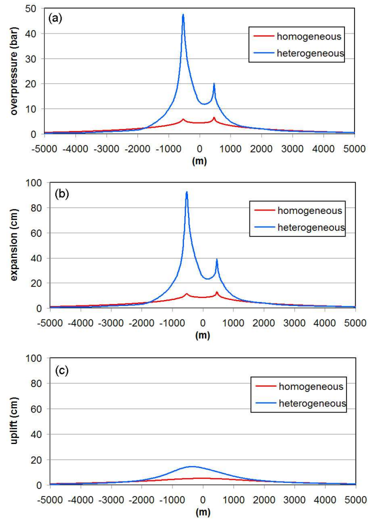

Figure 6. Comparison of the distributions of (a) over-pressure, (b) aquifer expansion, and (c) surface uplift along a cross section comprising two wells obtained in the worst-case K scenario and in the homogeneous case.

While the assumption of homogeneity leads to underestimating the aquifer expansion and its irregularities, these effects are substantially abated by the overburden, which spreads the vertical deformation over a larger surface area.

4 CONCLUSIONS

- The CDF's obtained from the stochastic analyses reveal that, for any choice of realistic geostatistical parameters, nowhere the differential vertical displacement exceeds the most severe regulatory limits required for building safety, the largest displacement gradient measured in Venice over the period 1961-1969, and the local displacement gradients currently underway in some areas of Venice.
- Even under the most extreme and unlikely realization obtained with σ^2=1 and λ=1000 m, where K varies over eight orders of magnitude, the maximum ρ_z is of the same order of magnitude (about three times larger) as the value computed using a deterministic approach with homogeneous K equal to the median value of the heterogeneous distribution. Therefore, the uncertainty connected to heterogeneity of the hydraulic conductivity in the injected formations can be viewed as a minor issue in a realistic prediction of Venice uplift by seawater injection.

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