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Statistical approach to damage diagnosis of concrete dams by radar monitoring: Formulation and a pseudo-experimental test☆

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Abstract

This paper deals with the investigation of a diagnostic procedure especially suited for large concrete dams. The main features of such methodology are as follows: static excitation of the dam; displacement monitoring by radar device; identification of the unknown Young moduli in pre-defined homogeneous zones through a batch least square method. The uncertainty of the identified parameters is assessed by means of a thorough statistical processing. The numerical validation of the proposed method is carried out on the basis of pseudo-experimental data. The most important results, summarized in the paper together with some computational remarks, are critically examined.

Keywords: Damage diagnosis; Concrete dams; Radar monitoring; Inverse analysis; Monte Carlo simulation

1. Introduction

Almost one half of the large concrete dams registered by the International Commission on Large Dams (ICOLD) are more than 50 years old. According to a report on the accidents occurred to dams in 29 countries [1], about 1% of the 4663 considered dams suffered failures and many others needed major repairs in order to preserve structural integrity. Many of these dams exhibit concrete deterioration, which means loss of strength, stiffness and other physical properties of materials. The causes of damage are of different nature; one of the most important, in particular in Europe, is the alkali–silica (called also alkali–aggregate) reaction. Alkali–silica reaction (ASR) in concrete is a chemical reaction that involves alkaline cations (Na^+, K^+, Ca^{2+}) in the cement paste, hydroxide ions (OH^-) and some sort of silica contained in the aggregates. The reaction produces an expansive gel, which diffuses in the connected pores and generates local microcracks and global expansion. The presence of ASR implies negative effects on overall mechanical properties of structural importance such as strength in tension and compression and stiffness (i.e. Young's modulus). Some discrepancies can be noted between results obtained with accelerated experimental tests performed by different researchers. For instance, no substantial reduction of strength was observed in the tests carried out by Larive [2]. In contrast, Swamy and Al-Asali [3] found that ASR can reduce initial values of compressive and tensile strength down to 60% and 80%, respectively. Similar results have been achieved recently by Ahmed et al. [4]. In any case, the reduction of the Young's modulus is widely recognized as the most representative indicator of the degradation induced by ASR.

The monitoring procedures and diagnostic analyses are of paramount importance in order to keep under strict control the mechanical performances of the materials that constitute the dam (see e.g. [5] and the web-site http://nw-ialad.uibk.ac.at). Damage diagnosis rests primarily on several in situ and laboratory experimental procedures, focused on the identification of local properties, e.g.: penetrometric tests (see [6]), customary for a long time in rock and soil mechanics; concrete coring and overcoring; flat jacks; permeability tests; chemical analyses; tomography through acoustic or ultrasonic measurements (see e.g. [7]).

Overall tests with static or dynamic excitation are frequently used in order to identify the space distribution of elastic stiffness as a meaningful parameter representative of structural

☆ This paper is dedicated to Professor Giulio Maier on the occasion of his birthday.

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damage. Dynamic inverse analysis combined with modal overall testing is perhaps the most versatile method for damage identification in many fields of structural mechanics (see e.g. [8–10]). Nonetheless, in dam engineering the results of dynamic tests can be significantly influenced by the following aspects: fluid–structure interaction, which can significantly change natural frequencies and mode shapes; foundation deformability, generally characterized by anisotropy and uncertain parameters; non-linear behavior of artificial joints and cracks (so called "natural joints").

A different approach, less common in dam engineering, is represented by static methods, thoroughly described in the recent review paper by Banan et al. [11]. When static excitation is exploited for diagnostic purposes, many among the previous drawbacks of the modal approach are avoided. In particular, the static approach is well suited for non-linear problems. However, some difficulties can arise: the static load could be not sufficient to properly excite the structure and the monitoring system could provide not enough information for the solution of the inverse problems. For these reasons some authors (see e.g. [12,13]) proposed a damage identification methodology which exploits the information achieved by static tests in order to enhance the performance of modal identification techniques.

This paper aims to demonstrate the effectiveness of a new procedure for global damage assessment based on static excitation, radar monitoring and inverse analyses in dam engineering. Some preliminary results, carried out within a deterministic framework, have been presented in [14,15]. Here, the attention is drawn to a statistical approach: numerical results in this sense are provided on the basis of pseudo-experimental data, generated with reference to an existing arch-gravity dam. Remarks on sensitivity analysis, parameter identifiability and computational aspects are also presented.

2. Structural diagnosis with static excitation

2.1. In situ instrumentation

In concrete dam engineering the most used displacement transducers are pendulums, which can measure relative displacements between two points on the same vertical straight line with high precision, say ± 0.05 mm. Other traditional instruments are the collimators: absolute displacements, in the horizontal direction normal to the line of sight, can be measured with an error of about ± 0.5 mm.

A new monitoring system, based on radar technology, has been recently developed (see [16,17]). Radar (acronym of Radio Detection and Ranging) is an active sensor that emits microwave impulses, records the back-propagated signals and, by measuring the temporal delay between the emitted signals and the received echoes, estimates the distance of the reflective objects. An important characteristic of radar sensors is the resolution, in the sense of minimum distance between objects that radar can distinguish. The Synthetic Aperture Radar (SAR) technique [18] requires that the radar sensor is moved along a straight line, performing several measurements using coherent impulses. The subsequent data treatment enables the construction of an image with high spatial resolution, because the movement simulates a wider antenna. A SAR sensor can measure absolute distances in a roughly approximated way, because of the intrinsic spatial resolution (more or less 30 cm). In contrast, if a reflecting point changes its position, it is possible to measure its displacement with a much higher precision by exploiting information on the signal phase, namely by interferometric techniques applied to subsequent images in order to achieve a precise map of the displacement field of the observed zone. Such a methodology, called Differential Interferometric Synthetic Aperture Radar (DInSAR), provides the following advantages: (i) remotely sensed measurements of a great number of points; (ii) no need of targets to be positioned on the monitored structure or landslide; (iii) independence from the weather conditions; (iv) high precision of the achieved measurements. According to recent information [16], the displacements of a structure can be estimated with an absolute error of about ± 0.25 mm.

Drawbacks and limitations of the DInSAR techniques are pointed out in what follows: (a) only displacement projection along the line of sight (i.e. the line connecting the radar and the monitored point) can be measured; (b) exogenous sources of error can be due to the loss of coherence in subsequent images; as an example, when performing measurements in different times, it is possible to locate the instrument in a slightly different position, with detrimental effects on the interpretation of phase change; this problem, however, can be easily identified and a posteriori corrected because it yields a systematic error on the acquired image; (c) displacement maps are strongly influenced by the reflectivity characteristics of the monitored object; in general, this problem is evident for natural slopes, whilst the situation is quite good for buildings and dams, endowed with highly reflective surfaces.

DInSAR has been already successfully used in dam engineering. A test has been performed on the arch-gravity dam located in Ridracoli, Romagna, Italy (see [19]). The measurements have been recorded periodically, every second week, achieving excellent agreement with the traditional monitoring techniques. The radar apparatus appears especially well suited for static damage detection in dam engineering, because of the capability to provide a large amount of accurate measures.

2.2. Operative and "direct" computational procedures

In overall static tests on a dam the external actions are represented by self-weight and hydrostatic load. The experiment starts from an initial situation of full reservoir; the water level is then decreased from the maximum to the minimum storage, in order to induce as large as possible displacements in the dam. The level lowering can be obtained either in a few days (about one week) by discharging the stored water through all the outlet devices, or by exploiting a seasonal oscillation between extreme service levels that are more or less close to the maximum and minimum values. In the former situation, which is considered herein, it is clearly possible in practice to neglect creep behaviour and thermal effects due to environmental temperature changes.