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REAL TIME TELEMETRIC MONITORING/EARLY WARNING SYSTEM OF LARGE DAMS

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Introduction

Large dams are complex structures with nonlinear dynamic behavior. Their safety depends on several factors (WIELAND, MUELLER, 2009). Engineers often are forced to assess dam safety based on the available incomplete data (SAVICH, 2002; SAVICH, 2006; CHELIDZE et al, 2011; CHELIDZE et al, 2013; BARTSH et al, 2011; BULLETIN…, 1989; BULLETIN…,2000), which is extremely difficult. This important problem can be solved with the modern theory of complex systems. It is possible to derive characteristics of the whole unknown dynamics of a structure using few data sets of certain carefully selected representative parameter(s). By means of high quality continuous records of some geotechnical characteristic(s) of a dam and modern methods of time series linear/nonlinear analysis the main dynamical features of the entire, unknown process (here-dam deformation) can be analyzed.

We created the cost-effective Monitoring Telemetric System for Dam Diagnostics (DAMWATCH), which consists of sensors (tiltmeters), terminal and central controllers connected by the GSM/GPRS Modem to the diagnostic center. The tilt data recorded for varying reservoir level are compared with static design model of dam deformations computed by a finite element method (FEM) for the dam-reservoir-foundation system. Besides, recently developed linear/nonlinear data analysis and prediction schemes may help to quantify fine dynamical features of the dam behavior. The software package DAMTOOL has been developed for this purpose.

The differences between measured and theoretically predicted response parameters of the dam may signal abnormal behavior of the object. The data obtained already by testing of the DAMWATCH/DAMTOOL system during operation of the high Enguri arc dam and reservoir (Georgia) show interesting long-term and short-term patterns of tilts in the dam body, which can be used for dam diagnostics. The proposed real-time telemetric monitoring (DAMWATCH) complex and linear/nonlinear dynamical analysis system (DAMTOOL) are unique.

Enguri dam international test area (EDITA)

The 271 m high Enguri arch dam, still the highest (in its class) dam in the world, was built in the canyon of Enguri river (West Georgia) in the 1970s. It is located in a zone of high seismicity (MSK intensity IX) and close to the Ingirishi active fault system (Fig. 1).

The high seismic and geodynamical activities together with a high population density of the adjoining region made the Enguri dam a potential source of a major technological catastrophe in Georgia. That is why in 1996 the European Centre "Geodynamical Hazards of High Dams" with the Enguri Dam International Test Area (EDITA) was organized in Georgia by the Council of Europe.

From the very beginning in EDITA the unique geotechnical, geodynamical and geophysical monitoring system (Fig. 2) was functioning (ABASHIDZE, 2001; ABASHIDZE et al, 2008). Several years before construction of dam geodynamical and seismological networks were created; so it is possible to compare the natural background state of seismicity and geodynamics with the impacts of dam construction and reservoir filling/ discharge processes

(Fig. 3). The database of observations (tilts, strains, etc.) contains information accumulated during more than 30 years.

Long-term diagnostic tools

1) The simplest approach to dam safety problem is to compare response of real strain/tilt data with design values, which as a rule use Hooke's linear-elastic constitutive model for mass concrete and rock. If measured characteristics, e.g., strains are close to or larger than theoretically predicted limit deformations, some preventive measures will be realized. However, the real engineering structures manifest deviations from this simple model.
2) From above it follows that a promising technique could be analysis of deviations from static elasticity model, namely, analysis of nonlinearity of stress-strain relation such as hysteretic behavior during load-unload cycle. Figure 3(a) shows how two components of tilts of dam body, along (X) and normal (Y) to the dam crest at Enguri Dam respond to the seasonal recharge-discharge cycle of the reservoir; on the right the hysteresis in seismic velocities of foundation section for the same cycle is shown.
It is evident that tilts (and consequently, strains) increase with loading and returning after discharge to the values close to initial ones following hysteresis path. The hysteresis in the cycle manifests presence of some nonlinear components of strain, which can be used for diagnostics of dam state as the nonlinearity is related to the presence of fractures. The problem is that not only the dam body, but also the upper earth crust (dam foundation) also manifests hysteretic response to load/unload process as well as thermoelastic stresses. We believe that the configuration and shifts of hysteretic cycles after separation of latter components can be used for dam state diagnostics.
3) In the rigid enough structure the theoretically calculated tilts/strains behavior in the time domain should be close to uniform in the definite areas/sections of the dam; strong local deviation from the correlated behavior of tiltmeters in some sections of the dam points to serious disruption of the dam elastic structure.
4) Other peculiarities of the load-unload process (timelag between water load and strains in the dam, details of strain build up and relaxation) also can be used for long-term diagnostics.
5) Fast change of strains during slow change of load can be a sign of closeness to the critical state–failure, caused by intensive generation of defects (CHELIDZE et al, 2006).
Mentioned diagnostic tools need relatively long time series of observations from days to months.

Short-term diagnostic tools

Besides above indicators there are some short-term features, which can be used for operative/express dam state diagnostics, namely:
1) Spectrum of natural frequencies of dam vibration (dam tremble), which are generated by various impacts such as water discharge, wind and wives, turbine rotation or ambient

seismic noise.

2) Amplitudes of various components of spectrum. It is well known that dams have some characteristic natural frequencies, which depend on peculiarities of dam structure, water level in the lake and on the damage rate of dam material. The record of natural dam vibrations at Enguri dam shows that the dominant frequency on the crest of the dam is about 1 Hz; this is in a good accordance with results of analysis of accelerograms during the last Racha earthquake (2005, M = 6) and linear elasticity theory, but our data show that the spectrum is much wider (Fig. 7(c)).

We believe that the dam vibration spectrum (amplitudes) (MIVENCHI et al, 2003) will respond to change of the state of dam damage (some frequencies disappear; new harmonics appear, etc.).

Real time telemetric monitoring systems of dams (DAMWATCH)

The M. Nodia Institute of Geophysics (MNIG) and Georgian-European Centre" Geodynamical Hazards of High Dams" operating in the frame of Open Partial Agreement on Major Disasters at the Council of Europe (EUR_OPA) are developing the cost-effective real time geotechnical telemetric monitoring system of large dams (DAMWATCH). This low-cost early warning system designed by MNIG and the company LTD "ALGO" (Tbilisi) consists of sensors (here - tiltmeters, APPLIED GEOMECHANICS Model 701-2) connected to terminal and central controllers and by the GSM/GPRS Modem -to the diagnostic center (Fig. 4). The innovation in comparison with similar systems, say that at the Coolidge dam (HOLZHAUZEN, 1991) is implementation of new methodology (nonlinear dynamics) for processing geotechnical time series and assessment/prediction of the dam behavior.

Theoretical basis and methodology

The main idea of diagnostics is that as a result of dam material/structure damage elastic properties of the dam body diverges from the predictions of the simple linear elasticity. Elastic properties of such materials, which are called inhomogeneous (disordered, diluted) at small concentration of defects (cracks, pores, voids etc) can be calculated by the theory of effective media (HILL, 1965) or at high density of defects -by the mechanical percolation theory (CHELIDZE et al, 2006).

Static (linear elasticity) approach — finite element model (FEM)

Standard static analysis of monitoring data was performed using dam-foundation 3D model (Fig. 5(a)), which is represented by isoperimetric finite elements (ZIENKIEVICH, TAYLOR, 2000), taking into account properties of foundation (by elasticity modulus) and geological fault in the right bank of canyon.

The weight of rock mass, including up to riverbed under-saturated surface, was taking into consideration by the uplift body force (1 t/m^3). The saturated surface was determined by model investigations. The seepage load on the grout curtain was determined as a difference of pressure between grout curtain and drainage. The hydrodynamic seepage force was taking into consideration in the nodes of foundation net by piezometric measurements.

Static FEM calculations were carried out with acting operating force, including weigh of dam; hydraulic pressure on the dam and canyon surface; seepage load in foundation in the reservoir operating level from 410 to 510 m. Figure 5(b) presents dam's maximal horizontal displacements to lower pond according to plumblines data from 1999 to 2005 (EMUKHVARI, BRONSHTEIN, 1991; ANALYSIS…,2008). The correlation between natural observations and theoretical calculation mainly at lower level of the dam is acceptable, but there are significant deviations in the upper dam levels (Table 1).

The most important is that the design model does not predict different (static) response to load and unload, i.e., existence of hysteresis phenomenon. The hysteresis in some works is explained by thermal effects (FEDERAL…, 1999.

Time series analysis and forecasting methods

To ensure operative statistical and dynamical investigation of dam stability problem, modern methods of linear and nonlinear analysis of strain/tilt time series are appropriate to use (PRESS et al, 1996; SPROTT, 2006; KANTZ, SCHREIBER, 1997; STROGATZ, 2000; MARWAN, 2003; MATCHARASHVILI et al, 2010).

Linear methods besides traditional statistical (moments, distribution testing) include frequency (power spectrum, autocorrelation function), time-frequency (wavelet transformation) and eigenvalue (singular value decomposition) methods of analysis of data sets (PRESS et al, 1996; SPROTT, 2006). Nonlinear methods of time series analysis include denoising of data sets (nonlinear noise reduction), testing of memory properties of targeted process (long range correlation testing, detrended fluctuation analysis (DFA), multifractal detrended fluctuation analysis; qualitative and quantitative evaluation of reconstructed from measured data sets phase space structures (correlation and information dimension calculation, Lyapunov exponents calculation, Recurrence Plots (RP) and Recurrence Quantitative Analysis (RQA), Shannon and Tsallis entropy (KANTZ, SCHREIBER, 1997; STROGATZ, 2000; MARWAN, 2003; MATCHARASHVILI et al, 2010). According to our experience assessment of stationarity (level of determinism) of investigated time series for different length moving windows is informative for tasks like targeted ones. The arguments for using suggested methods for dam safety analysis are: 1) the strains/tilts and other geotechnical parameters of dams manifest as a rule quasiperiodic variations in time due to seasonal load-unload cycle; 2) this means that dynamics of strains/tilts time series should follow relatively stable orbits in the phase space or just manifest relatively high level of determinism; 3) the significant deviation from the stable orbit or strong decrease of determinism can be considered as a sign of instability.

The big merit of the above approach is that nonlinear analysis of complex system may be accomplished based on analysis of correctly selected and high quality few or even one component data set (PEINKE et al, 2006; MATCHARASHVILI et al, 2008).

For practical use special package DAMTOOL has been developed, which allows calculation of DFA and RQA parameters for selected monitoring time series.

The suggested linear and nonlinear analysis methods are able reveal changes in dynamics of monitoring time series, which can be connected to the mechanical state of construction.

Mesoelasticity (nonlinear elasticity) approach

The theoretical interpretation of experimental hysteretic stress-strain or tilt-stress dependences at present is mainly taking into account thermal effects, though in our opinion it can be accomplished also by the theory of mesoscopic elasticity (McCALL, GUYER, 1994; GUYER, JOHNSON, 2009). The matter is that heterogeneous materials (concrete, rocks, etc) are nonlinear and their behavior is very different from this of its homogeneous components: for example, stress-strain (or tilt) of the system can manifest nonlinear hysteretic elastic behavior though its components have linear characteristics. Hysteresis is connected with specific response of so called mesoscopic structural features (mainly compliant micro-cracks) to stress variation, namely, asymmetric response to load and unload. Real heterogeneous materials contain enormous number (10^{9}–10^{12}) of such defects in a square cm, which means that macroscopic elastic properties of material depend strongly on behavior of microcracks. Thus parameters of hysteretic cycle can be used for diagnostics of material: in the absence of cracks the brittle solid manifests linear elasticity, appearance of cracks leads to hysteresis and the opening of hysteresis curve increases with number of defects. If the hysteresis cycle is reversible (curve returns to initial position after reduction of stress) then the system is nonlinearly elastic, but if the hysteresis curve shifts in some direction it can be a sign of appearance of residual strain. The formal approximation of experimental annual hysteresis data can be accomplished using Preisach-Mayergoyz (P–M) phenomenological model (GUYER, JOHNSON, 2009). In P–M model the system is represented by complex of hysteretic elastic units or hysterons; the unit can exist in one of two states, closed (having the length L0 at pressure P0) or open (having the length Lc at pressure Pc). We can assume that Pc > P0 and accordingly L0 > Lc,which corresponds to closing of existing cracks at rising pressure P from P0 to Pc (Fig. 6(a)) At decreasing pressure the hysteron opens at P0 and remains in this state at even lesser pressures. Such approximation means that the change of state of hysteron (namely, of its length L) depends on the pressure history: transition from Lc to L0 takes place at pressure Pc, but the backward transition from L0 to Lc occur at pressure P0. The heterogeneous material can be modeled by a system of many hysterons with random distribution of parameters P0, Pc, L0 and Lc. TheP–M space consists of elements with different pairs of Pc and P0, thus Pc and P0 can be considered as XYcoordinates of P–M space (Fig. 6(b)). The part of elements is located along the diagonal of P –M space, where P c= P0; these elements 1 close and opens at the same pressure, which means that they are not hysteretic; the remaining hysterons with Pc ≠P0 populate P–M space with varying density of states of open or closed hysterons; the points in P–M space are generated randomly according to some simple rule. The hysteron described above corresponds to closure of 1 (existing) open cracks at raising pressure, i.e., this is the case of relatively low pressures. At high pressures, close to material failure, the hysteron pattern is reversed, namely, in this case at Pc > P0 the length of hysteron increases from L0 to Lc,. The standard P-M model describes the case of reversible hysteresis, i.e., the hysteresis loop begins and ends at the same pressure, which means that the initial state of the system can be restored. In real systems besides elastic strain there is also often residual deformation, which means that at repeating load-unload cycles the shift of hysteresis loops will happen. The shift of hysteresis loops can be used as a measure of residual strain (damage rate) in a given material. Comparison of Figs. 3 and 6 leads to conclusion that observed phenomenon of dam tilts/strains hysteresis can be used for quantitative assessment of dam damage state.

The first results of monitoring

Long-term data and Static model

Of course, predictions of the model have to be compared with monitoring data. The generally accepted approach is to compare the observed stress (strain) to calculated stresses, which correspond to some fraction of yield strength or of the ultimate strength of the material which the construction is made of.

Though high tensile stresses in concrete are the most destructive factors (they generate cracks at 5–10% of uniaxial compressive strength of the concrete) the combined action of water load and dam dead load results in the dominating role of compressive stress under static load conditions; only under oscillating forcing tensile stress became equal to the compressive one. As for static tensile stress, its maximal value is observed generally along the upstream heel of arch dams. "The ultimate load-resisting capacity of an arch dam is limited by the compressive strength of the concrete (unless foundation or other mode of failures occur first), but severe and widespread joint opening and cracking might eventually exhaust the capacity of the concrete to carry compression due to subsequent load redistributions" (FEDERAL…, 1999).

Regarding Enguri dam, according to Ref. [15]. the diagnostics of dam safety considers three versions: diagnose 1 – normal state (N); diagnose 2 – maximal allowable strain (MAS); diagnose 3 – pre-failure strain (PFS). Diagnose MAS implies that deflection of dam response (strains) to acting loads exceeds theoretical values, which means that object needs detailed investigation by special program, though the exploitation of the dam can be continued as usual and diagnose PF means that after repeated investigation exploitation regime should be changed up to full shutoff.

Table 1 presents observed plumbline horizontal displacements (ANALYSIS…, 2008) and corresponding tiltmeters' data (horizontal displacements in mm and tilts in seconds, with Root Mean Square) at maximal water level in the lake (510 m) for three sections of Enguri HPP (ABASHIDZE et al, 2008) with theoretical (critical) admissible values of plumblines calculated by (EMUKHVARI, BRONSHTEIN, 1991). Values of theoretical (critical) admissible values of plumblines given (EMUKHVARI, BRONSHTEIN, 1991) are calculated based on the stress state and concrete strength and mark the border between normal and "faulty" state of the dam. Analysis of the Table leads to following conclusions: 1) At the level 360 m all displacements are less than critical values; 2) at the level 402 m only in the central 18-th section the displacements are close to critical ones; 3) at the highest level (475 m) displacement of the side sections are larger than critical, i.e., at this level the state should be considered as diagnosis MAS or "faulty". According to (EMUKHVARI, BRONSHTEIN, 1991) in this case it is necessary to carry out repeated diagnostics of construction on the basis of re-examination of monitoring data and correction of theoretical predictions of response of the dam to loads. The displacement observation data obtained by two different methods are in satisfactory agreement.

As far as the dam performs normally and there are no visual signs of significant damage we presume that the theoretical model needs corrections, possibly taking into account complexity of construction structure (existence of lifts, joints, cracks, nonhomogeneities, etc.), which is reflected also in the phenomenon of hysteresis (Fig. 3).

Uncertainity of static data and long time (year) needed for safety assessment calls for developing new more efficient and operative methods, which are considered in following sections.

Time-dependent methods

Figure 7(b) presents the results of monitoring of X and Y components tilts of the dam body on three levels of section12 of Enguri dam, at levels 475 m (X3, Y3), 402 m (X2, Y2), and 360m (X1, Y1), see Fig. 2(c). The first months the data were collected with the rate once per minute: this allows catching short transient effects, which can be useful in diagnostics.

Several effects were observed during operation of DAMWATCH: tilt oscillations with a period of one to several minutes or "low frequency (LF) dam tremble," sudden variations of dam tremble amplitudes, strong solitary peaks with relaxation period of several tens of minutes, stepwise change of tilts, daily variations and slow variations lasting months/years.

1) Analysis show that strong solitary peaks marked in Fig. 7(b) by date and time are caused by power cuts, so these effects should be neglected as artifacts. 2) LF dam tremble is most intensive for both components close to the dam crest (components X3, Y3), but is visible on other levels also, especially at fast water discharge (Fig. 7(a)). The tremble recording does not look as a white noise. It seems to be related to the state of construction, as its amplitude responds to the drastic increase of water discharge, realized through the body of dam at the level 330 m. In Fig. 7(b) mark moments of water discharge exceeding 200 m^3 per second. The origin of drastic increase of dam tremble on 17 May is unknown, as the discharge this day was not intensive. 3) Daily variations are well expressed on the recordings of both components (X2,Y2) of tiltmeter installed in the middle of dam and also with less intensity at the lowest level (X1,Y1) (Fig. 7(b), Fig. 8(b)). As the amplitude of daily variation did not change after thermal isolation of device by foam plastic boxes, the direct effect of ambient temperature on the device (artifact) is excluded. These variations can be caused by daily water level variations, or thermoelastic response of the dam structure to ambient temperature, or earth tides. Further studies are needed to establish source of daily variations.

4) Intermediate-term (weeks, months) water level variations. It is evident that water level change (Fig. 8(a) and medium-term tilt variations (Fig. 8(b)) are closely correlated and they can be used for diagnostics of dam response to lake load.

Note that this correlation is visible only on the level 402 m, which can be explained by relatively high response to a water load at the middle part of the dam, predicted by its design.

5) Long-term/annual circles. Comparing outputs of Preisach-Mayergoyz model with annual hysteresis loops of Enguri dam tilts (Fig. 3(a) with Fig. 6) we can mark close similarity between model and observed data, i.e., P– M approach can be used in dam diagnostics. The successive annual Enguri tilt loops are shifted, which means that load-unload cycles involve appearance of some residual strain and this shift also can be a diagnostic sign (say, to assess aging effect). Of course, nonlinear contributions to stress-strain dependences are not very significant. That is why the dam design funded on linear approach works quite well, but analysis of nonlinear effects can produce promising methods of dam safety diagnostics.

Other experimental data

7.3.1 Earthquakes (EQs)

The relatively high frequency (HF) vibrations of dam in the range of 1–5 Hz due to earthquakes are extensively recorded by accelerometers and used for stability analysis. Record of the October 6, 2005 Racha event M = 6 occurred at the distance 100 km was obtained at Enguri dam. The seismograph recordings were made at several places near the center of the crest (Fig. 9). One of the horizontal components was oriented perpendicularly to the crest. Several recordings with duration up to 30 min have been done on the crest of the dam. The records were analyzed, amplitude and power spectra have been calculated using software package PITSA and MATLAB. Analysis of records shows that two mean frequencies can be identified ~1.6–1.7 and ~2.1–2.2 Hz. This result is in good agreement with theoretical studies and is close to results, obtained on other dams with similar characteristics. That means that for relatively high frequencies the dam response is elastic, unlike its response to slow strains.

Besides, for the rough estimation of natural frequency of the dam special experiment was carried out using sensitive seismographs. It is well known that dams have some characteristic natural frequencies, which depend on peculiarities of dam structure, water level in the lake and on the damage rate of dam material. This last feature can be singled out from observations if other characteristics are kept constant. Installing sensor on the crest of the dam, we can estimate quite precisely the main mode (and in some cases fist modes as well) of dam natural frequency. The Lenarts short period seismograph has been used. The structure subjected to a near white-noise ambient excitation responds primarily in the vicinity of its resonant frequencies. These frequencies can be identified from the peaks in power spectral densities (PDW) computed from the individual time histories.

The record of natural dam vibrations at Enguri dam shows that dominant frequency (main mode) on the crest of the dam is about 1 Hz, this is in a good accordance with results of analysis of accelerograms during the last 2005 Racha earthquake (Fig. 9).

Usually the main short-term diagnostic tool is the analysis of the eigenfrequencies of the dam based on the power spectra of dam vibrations caused by water discharge, turbine operation or ambient seismic noise. Note that the turbines of Enguri PP are located far from the dam and thus the vibrations are due only to dam exploitation and some environmental processes. At the same time our data obtained by 701 platform tiltmeters (Applied Geomechanics) at high sampling rate (1per minute) show that EQs excite vibrations at the much lower frequencies also. The analysis of frequency response spectra of platform 701 tiltmeter shows (Fig. 10) that the network consisting of such tiltmeters and ambient seismic noise recorders allow monitoring of dam vibrations in very wide range from 100 Hz to a quasi static state, which extends significantly the frequency range of non-broadband seismic devices: this can give enormous additional information on the dam state. This is demonstrated by recordings of remote and local earthquakes obtained during our experiments. Figure 11 present recording of tilts response to the moderate local EQ (Vani, M = 5.3, 19.01.2011), which occur at the distance 80 km from the dam and Fig. 12 presents expanded recording of the event. The EQ generated significant tilts, which differ for different sites of the dam and vary in the range from 10 to 15 s (X7, Y7, X3)to2–3s (Y2, X5, Y5). The event was fixed well due to the relatively high sampling rate (1/min); at the sampling rate 1/hour it could be missed.

It is interesting to note that 13 h before Vani EQ there was a long tremor on all sensors – its duration was 30 min and period of order of minutes. There was no significant strong EQ in the world these days so contribution of long period seismic waves is excluded (may be this was local slow/silent precursory EQ?). The tremor generated tilts in the range from 2 to 3 s (X7, Y7) to1s(X5, Y5).
Besides local Vani EQ, strong remote EQs also cause very low frequency (VLF) vibration of dam. 11 March 2011 the great Tohoku M = 9 EQ stroke Japan. Tohoku earthquake epicenter is separated from Enguri by 7800 km. Nevertheless, the EQ was so strong that the Enguri dam experienced quite appreciable shaking (Fig. 13), just at the moment of arrival of seismic waves from Japan to Enguri, according to Georgian seismic network data. Unfortunately that time the sampling rate was only 1/10 min and the record of shaking show less details than record of Vani event. The wave trains of Tohoku EQ, presumably, slow surface (Love and Rayleigh) waves, induced on all levels of the dam observable tilts in the range 2–3 angular sec; maximal tilt was recorded at the X1 component – 4s. Duration of the tilt perturbation was of the order of 130 min. The presented tiltmeter recordings of EQ at low sampling rate do not represent adequately the whole spectrum of dam response, but the data at high sampling rates of the order of 1 per sec corresponding to long-period surface waves from distant earthquakes can give very useful information on the dam state, as the defects of dam structure affect mostly low frequency respond.

Seiches

It is well known that in an enclosed body of water (lakes, reservoirs, bays, harbors) a standing wave or seiches are generated by disturbances of water body by wind, earthquakes etc. These standing waves cause time-depending deformations in the dam body. Such effects were observed on the Enguri dam. The seiche-generated vibrations were recognized by their co-incidence with strong winds, recorded by meteorological station. As the amplitude of some tilt perturbation of duration from tens of min to hours strongly (almost to zero) decreases at lower levels of dam, the most probable source of perturbations (Fig. 14) are waves in the lake due to wind (seiches).

The clear example of wind-related perturbation in dam tilts is presented in Fig. 14: readings from 1 to 171 (arrow) correspond to calm weather (MeWV – 0.2 m/s, MaxWV –3.6 m/s, WD – ENE and readings from 171 to 292 – to stormy one (MeWV – 2–5 m/s, MaxWV – 15.2–16.5 m/s, WD – N-NW). Here MeWV is the mean wind velocity, MaxWV-maximal wind velocity, WD means wind direction, ENE means East-Nord-East and N-NW means Nord-Nord-West accordingly.
According to theory the longest natural period for a seiche in an enclosed rectangular body of water is usually represented by the formula: $T = 2L/\sqrt{gh}$ where L is the length, h the average depth of the body of water, and g the acceleration of gravity. Inserting data for Enguri lake L = 25 km, h = 50m we get T = 38 min, which is close to observed values (Fig. 14(b)). In principle the seisches-generated LF vibrations can be used in dam diagnostics, as their frequency should depend on dam state.
Besides "normal" seiches there were observed vibrations of much lower frequency — presumably, very slow seiches with period of order of several hours.

Intensive water discharge

Discharge of excess water trough a slide gate (dam outlet) also causes tremors in dam body: their signature is maximal intensity in the middle level of dam and smaller intensity at both upper and lower levels (Fig. 15). The characteristics of such tremors also can be used for diagnostics.

Examples of application of nonlinear dynamics technique

To test sensitivity of selected linear/nonlinear methods of analysis of monitoring data recorded in the foundation of dam and asses effects of external influences on Earth tilt dynamics in the dam foundation, we considered tilt data sets in the following seven time windows for Enguri HPP: 1) Long before reservoir filling, 2) immediately before and 3) just after beginning of filling, 4) after second, 5) third and 6) fourth stage of reservoir filling and 7) long after completion of reservoir filling, i.e., during regular exploitation regime. Figures 7(a) and (b) illustrate RQA determinism (RQA%DET) and Lempel-Ziv algorithmic complexity measure for mentioned 7 periods. It is evident that for different stages of dam construction and reservoir fill significant quantitative differences have been detected in the recurrence attributes of phase space structures reconstructed from tilt data sets. Note that nonlinear dynamical properties of tilt time series during regular (periodic) reservoir exploitation return to the patterns observed before the dam building and lake fill (see bars 1 and 7 in Fig. 16). Thus our analysis confirms possibility of detection of man-made effects in tilt time series.
It is interesting that the local seismicity follows the similar pattern: the degree of determinism in seismic time series decreases in time windows 2–6 and returns to initial values long after filling.
Besides this long-term test the nonlinear dynamics software module DAMTOOL for short-term visual control, processing and nonlinear analysis of monitoring data (e.g. tilt time series) of engineering constructions has been developed. Fig. 17 demonstrates potential of nonlinear dynamics approach to analysis of tilt time series from April 2010 to June 2010. Figure 17(b) shows results of calculations by DAMTOOL package of RQA percent of determinism or RQA %DET (MARWAN, 2003) and Fig. 17(c) the same for Detrended Fluctuation Analysis or DFA [28]. The deviations from the normal behavior in the mid-

May and June are evident even visually, but the usage of DAMTOOL allows assessing these deviations quantitavely. Note high values of spectral slope (DFA) and %DET during regular regime in April and first decade of May (which points to stability of monitoring data) and strong deviations due to geotechnical impact – addition of high frequency component due to intensive discharge of water through dam outlet in 12.05–22.05.2010 and 01.06–11.06.2010 time intervals (Fig. 7 (a), (b)).
Thus, the disruptions in monitoring time series determinism can be caused both by construction damage and by usual geotechnical procedures.

Conclusions

Automatic Real-Time Telemetric System for Dam Diagnostics (DAMWATCH) is installed at Enguri Dam International Test Area (EDITA). System consists of tilt sensors connected to terminal and central controllers and by GSM/GPRS Modem -to the diagnostic center. The important component of the system is the nonlinear dynamics module DAMTOOL for analysis of monitoring (say tilt) time series.
The tilt data for varying reservoir load were compared to (static) theoretical model of dam deformation computed by finite element method (FEM). The results for the lover levels of dam (close to foundation) are satisfactory, but displacements for the crest area exceed theoretical assessments. At the same time it is evident that dam is operating normally, which means that the theoretical model needs corrections, possibly taking into account complexity of construction structure (existence of lifts, joints, cracks, nonhomogeneities, etc.), which is reflected also in the phenomenon of hysteresis.
Besides static approach, the nonlinear analysis of low-frequency vibrations data can be used to detect changes in dynamics/stability using dam tilts/strains time series. Corresponding package for linear/nonlinear analysis of monitoring time series (DAMTOOL) has been developed. The arguments for using suggested methods for dam safety analysis are: 1) The strains/tilts and other geotechnical parameters of dams manifest as a rule quasiperiodic variations in time due to seasonal load-unload cycle; 2) this means that dynamics of strains/tilts time series should follow relatively stable orbits in the phase space or just manifest relatively high level of determinism; 3) significant deviation from the stable orbit or strong decrease of determinism can be considered as a sign of instability after excluding man-made effects.
The data obtained already show very interesting long-term and short-term patterns of tilts' dynamics in the dam body, including tilt hysteresis during annual loading-unloading cycle, low-frequency dam oscillations etc, which can be used for dam diagnostics. The possible interpretation of hysteresis phenomena by mesoelasticity (nonlinear elasticity) approach is suggested. It is shown that the main contribution to annual tilts hysteresis comes from the dam body tilts, thus these data are appropriate for dam damage diagnostics. The tiltmeter recordings with one minute resolution reveal many interesting details of dam behavior, which expand the spectrum of dam vibrations to low frequencies and give new diagnostic tools. Analysis of retrospective tilt data show that used methods are appropriate to detect and quantify dynamical changes in dam body behavior caused by different external and internal causes, though mechanism of some observed effects still need to be studied in detail.

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Images

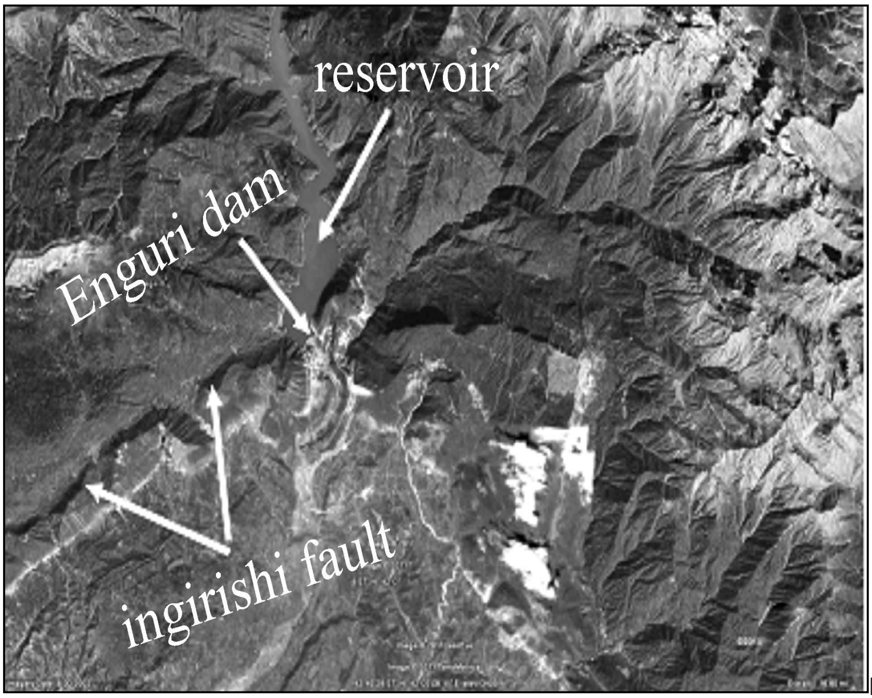


Fig.1. Space image of Enguri Dam International TestA rea(EDITA)

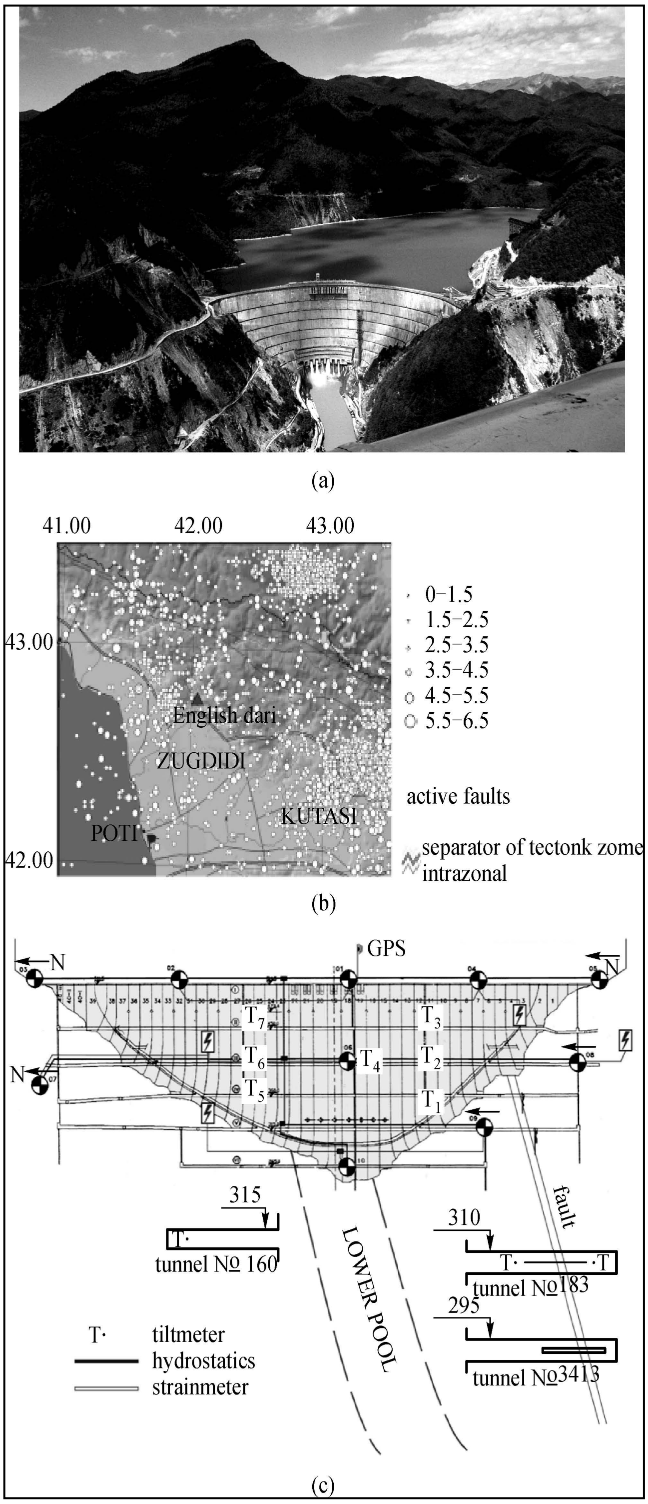


Fig. 2. (a) Downstream view of Enguri Dam; (b) map showing location of EDITA and patterns of local seismicity; (c)scheme of monitoring network at EDITA, numbers show location of accelerometers and T–location of tiltmeters(downstream view)

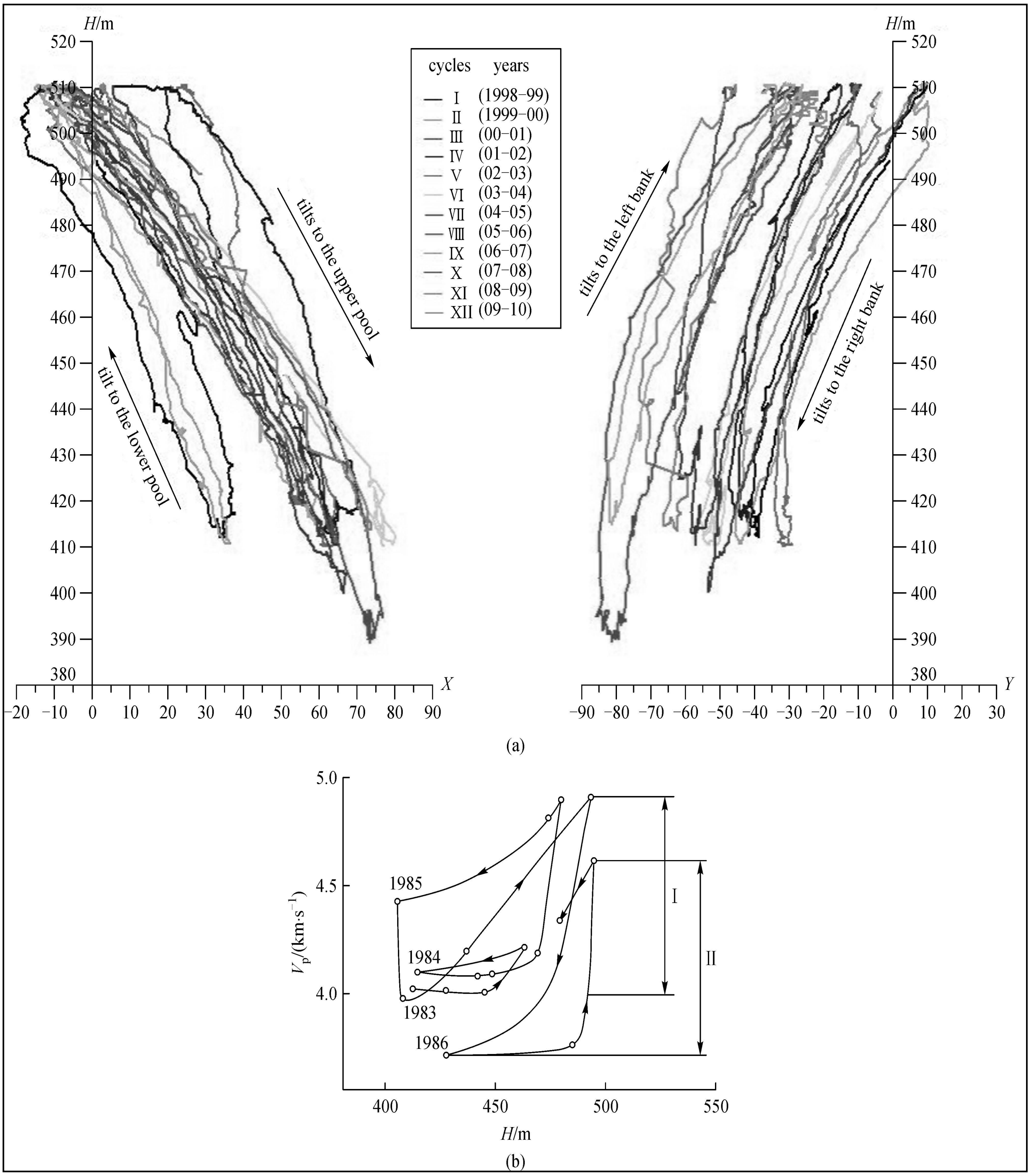


Fig.3 (a) Tilts in sec, registered in the body of Enguri High Dam, Georgia (section12,mark402) in two directions, along (X) and normal (Y) to the dam crest versus water level in the lake H in meters

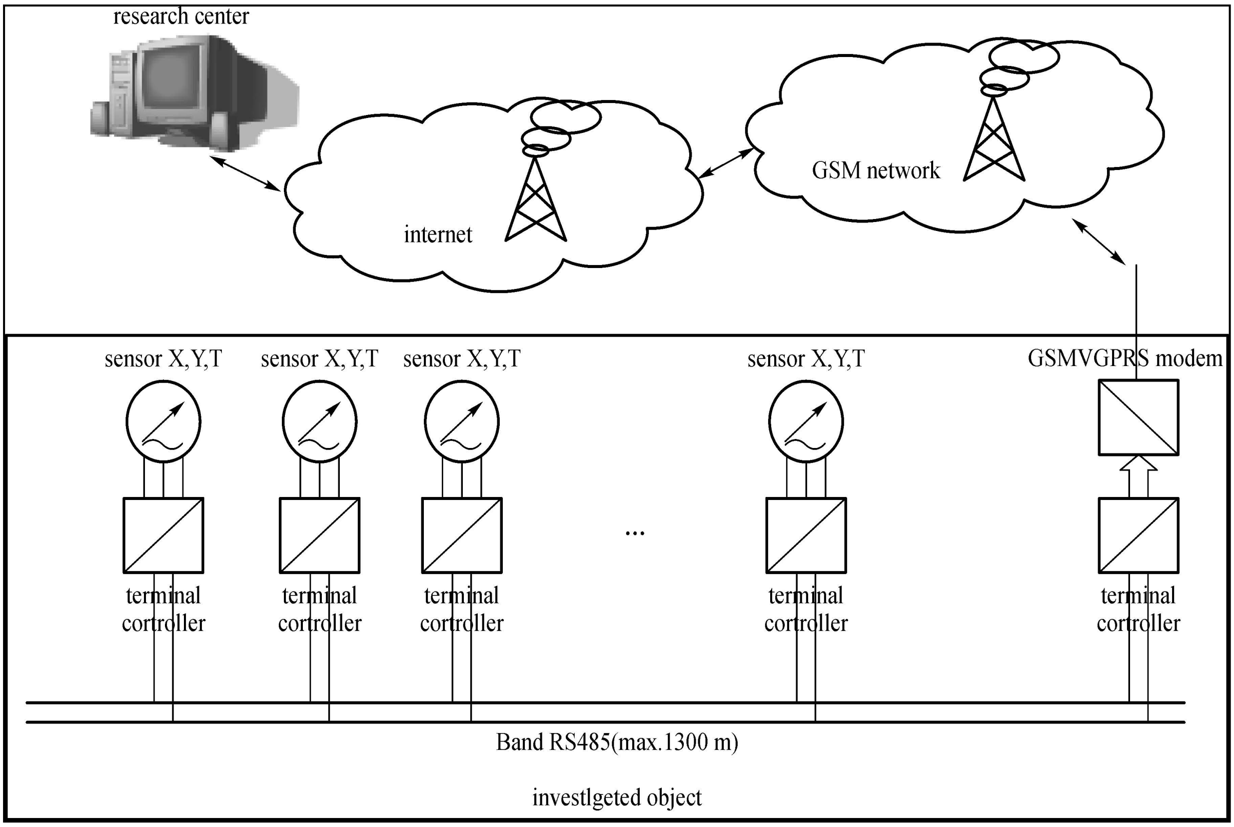


Fig.4. The cost-effective early warning system designed by MNIG and "ALGOLtd" (Tbilisi) consists of sensors (tiltmeters APPLIED GEOMECHANICS Model701-2), which are connected to terminals and central controllers and by a GSM/GPRS modem transmits the data to the diagnostic center.

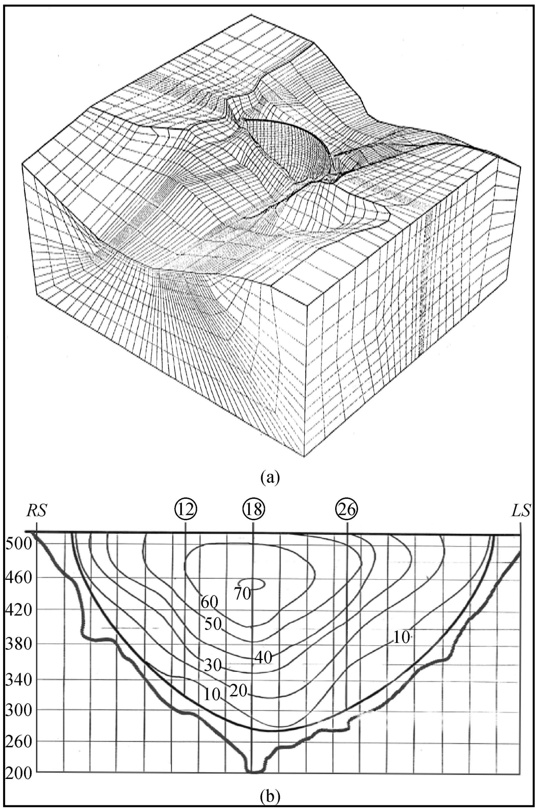


Fig. 5 (a) 3D model of dam-foundation system; (b) dam's maximal horizontal displacements to lower pond according to plumblines data (1999–2005); compare with Table 1

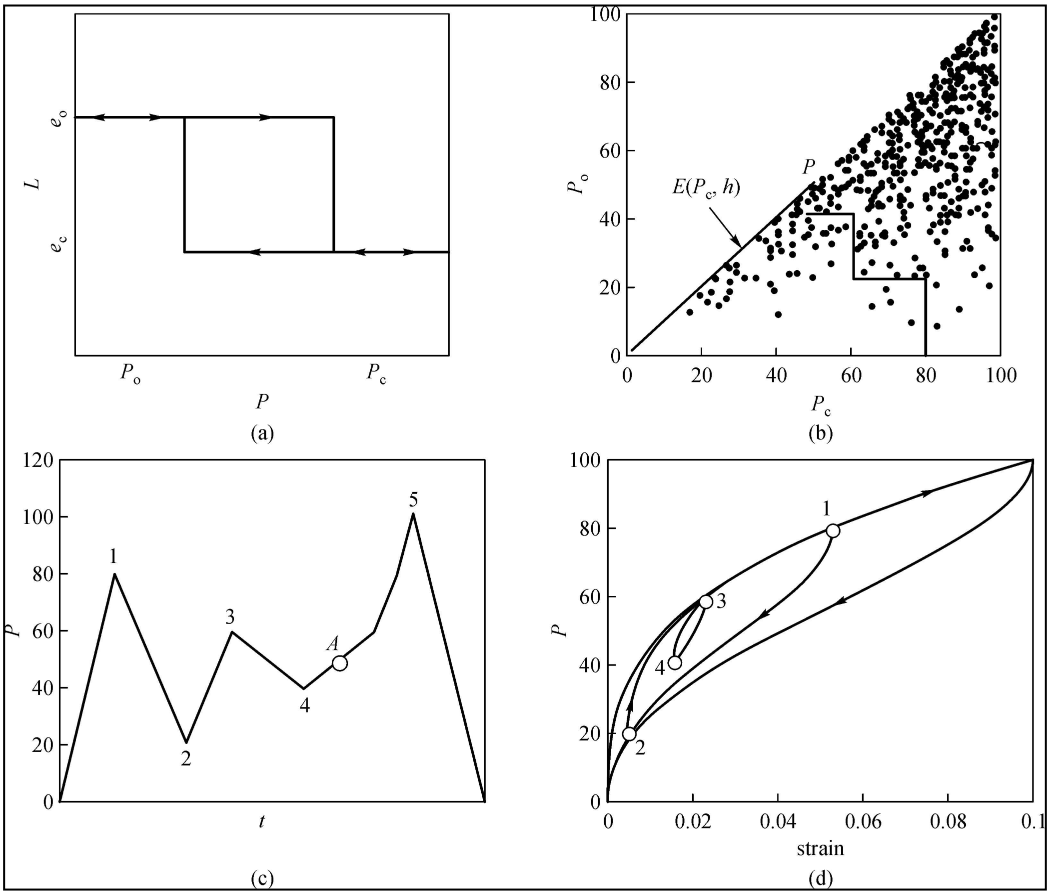


Fig. 6 (a) The P–M hysteron, characterized by a pair of pressures (P0 and Pc) and corresponding lengths (Lc and L0); (b) the points, representing pairs (Pc, P0) in the P–M space, generated by specific model equation; (c) the history of pressure applied to a system, containing many hysterons (pressure protocol); (d) the hysteretic stress-strain dependence corresponding to the above pressure protocol. Note the internal hysteresis loops, due to the pressure reversals at the points 1 and 3 [26].

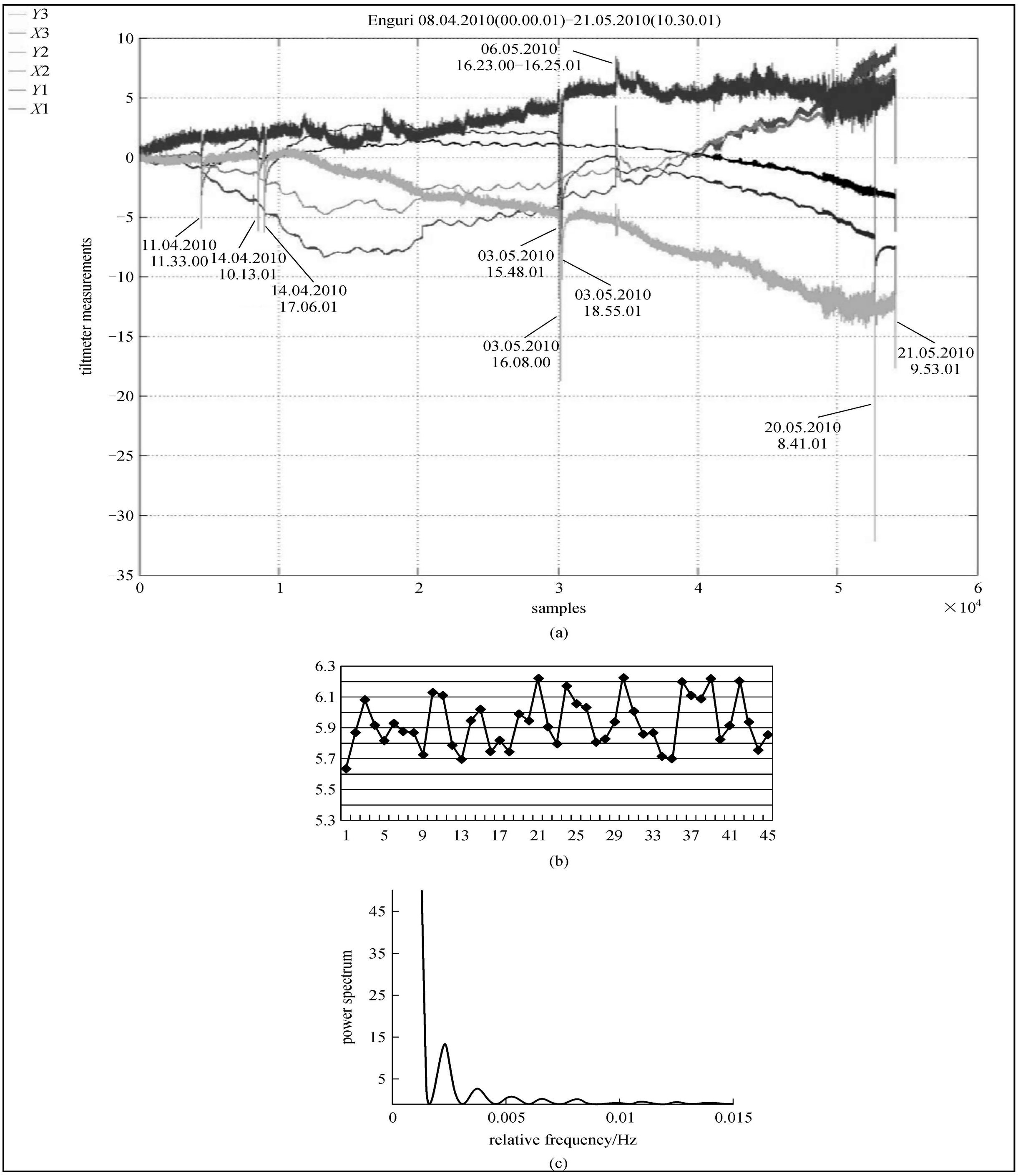


Fig. 7 (a) Tilt records of dam tilts (in sec) at three sites versus time (in minutes) from April 4 to May 21. 2010; (b) LF dam tremble– oscillations of Y3 component of tilt in sec versus time in minutes recorded by the tiltmeter in the section 12 at the level 475 m, part of record of 28.08.2010; note variations with a period of order of minutes; (c) power spectrum of Y3 component-the first maximum is at 6–7 min

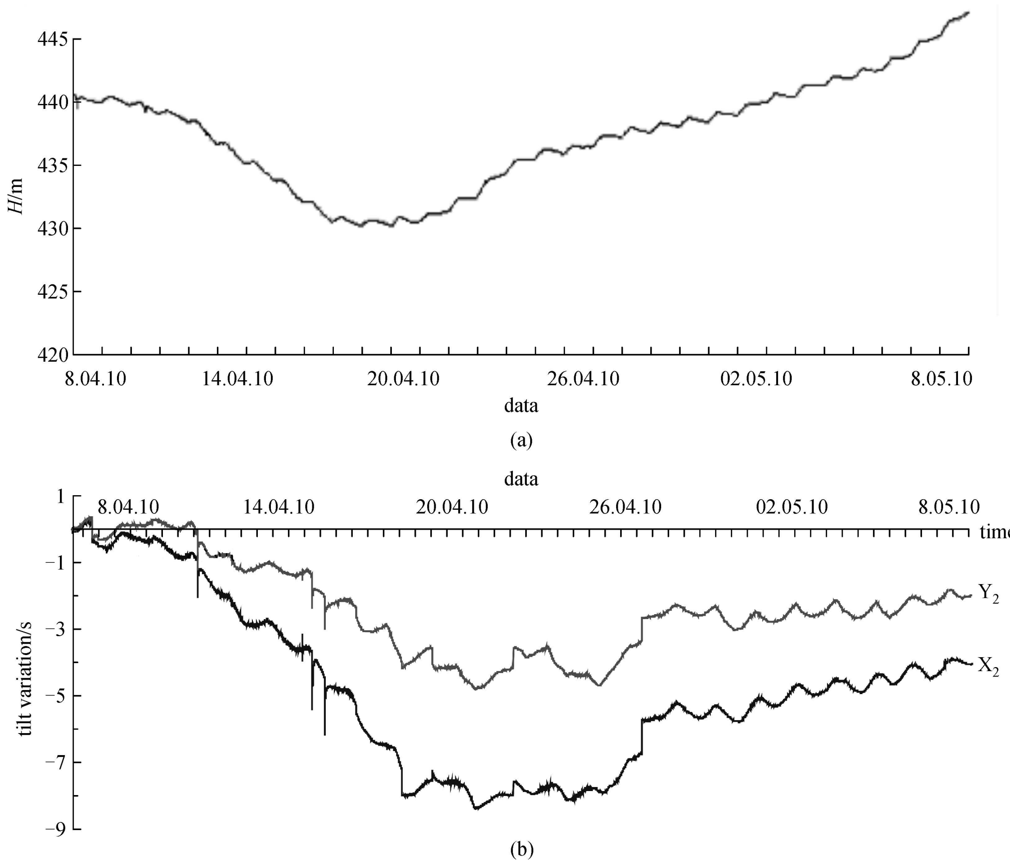


Fig. 8 (a) water level variations in Enguri reservoir, m (May 1–31 2010); (b) variations of tilts in sec (components (X2, Y2) in the same period. Note daily variations of tilts and water level.

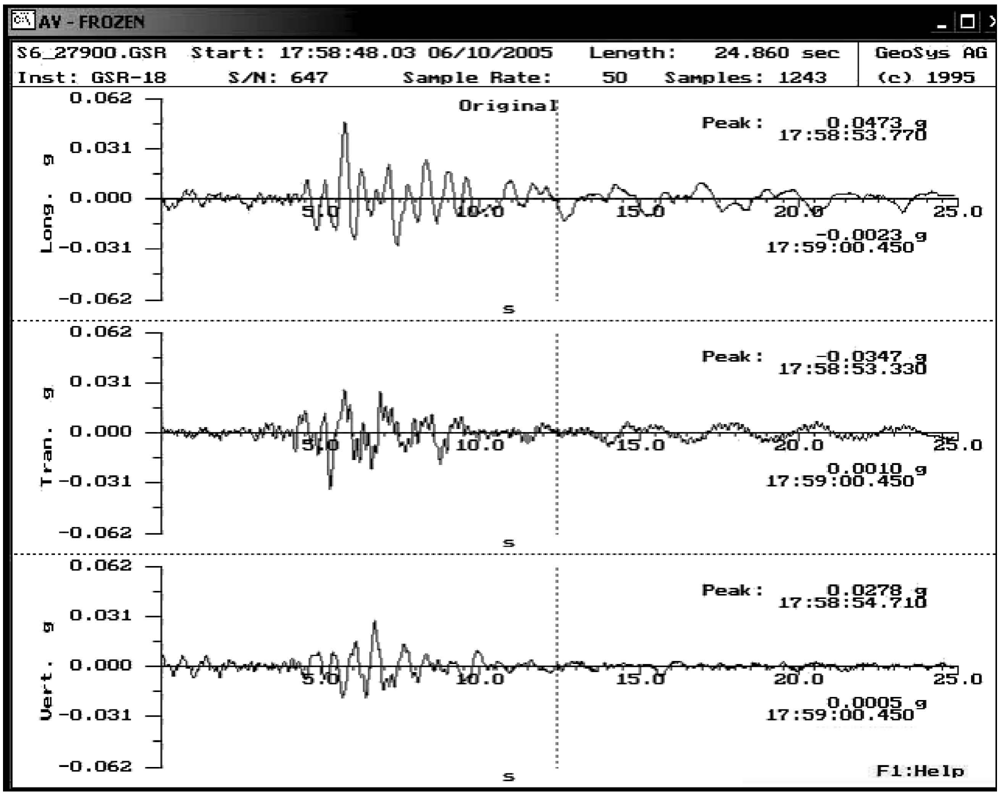


Fig. 9 Records of the October 06, 2005 Racha event M = 6 (distance 100 km) obtained at Enguri dam

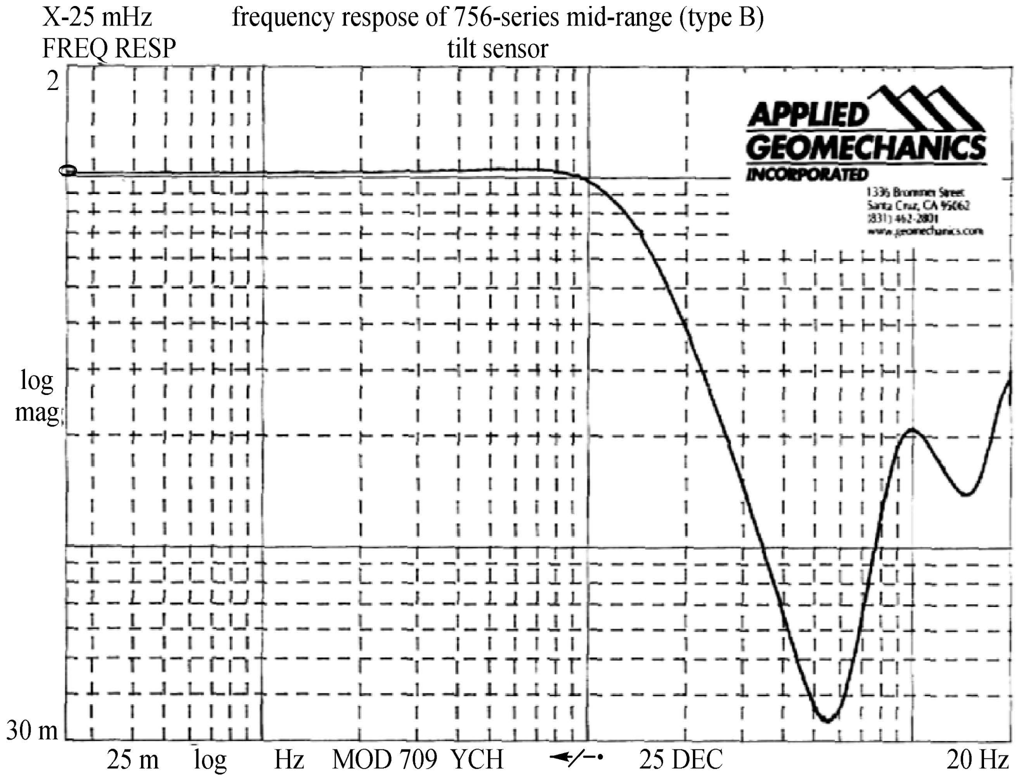


Fig.10 The frequency response spectra of platform 701tiltmeter (Applied Geomechanics)

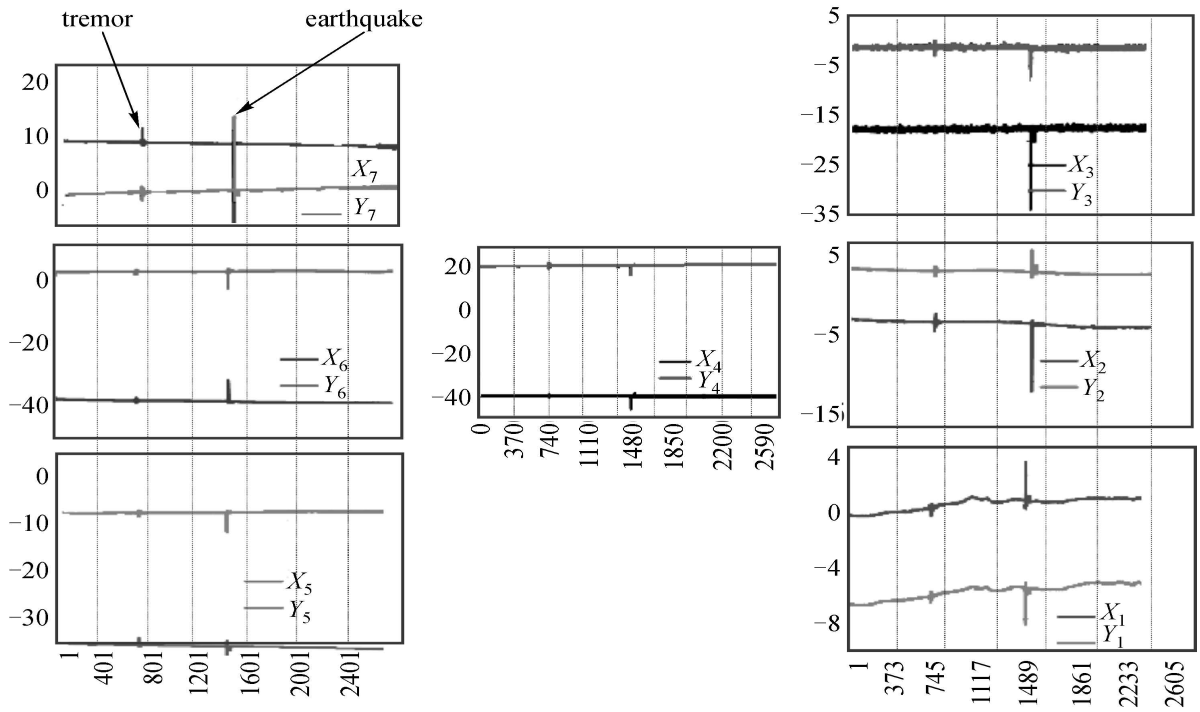


Fig. 11 Local EQ-Vani, M = 5.3, 19.01.2011 (distance to dam 80 km) and possible preliminary tremor (perturbation) 13 h before the EQ. Here and in similar diagrams location of figures corresponds to their location in the dam body (see Fig. 2(c)). Sample rate1/min

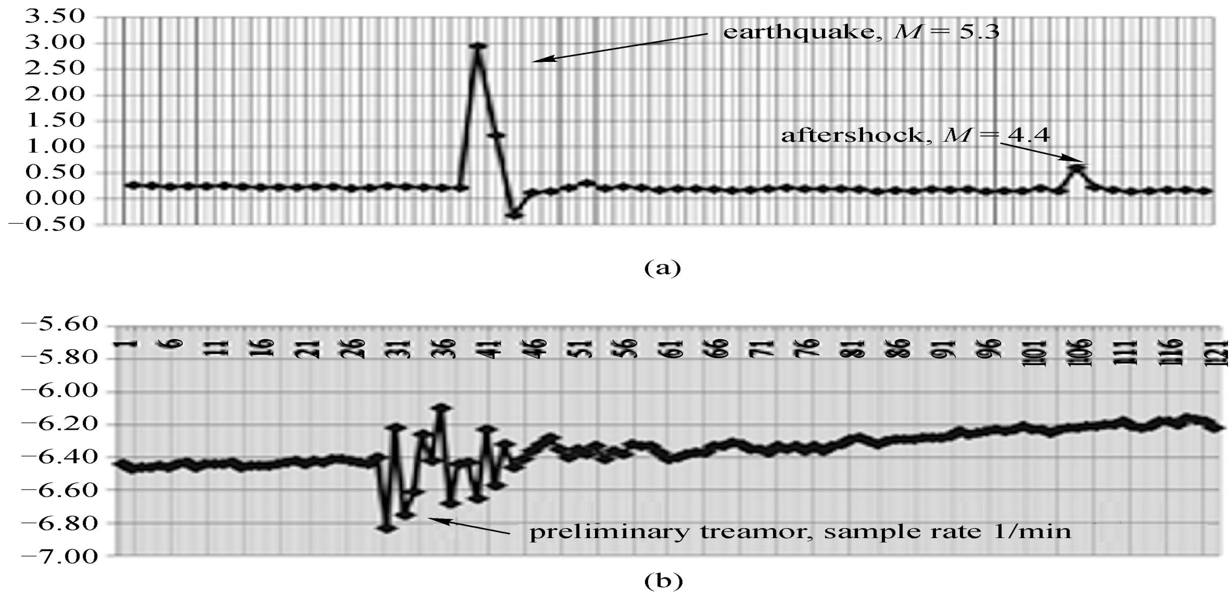


Fig. 12 Expanded record of tilts at Enguri dam to the Vani event. (a) Local EQ – Vani, M=5.3, 19.01.2011 (distance to dam 80 km) and aftershock M=4.4 ; (b) Preliminary LF tremor 13 hours before Vani EQ; sample rate – 1/min.

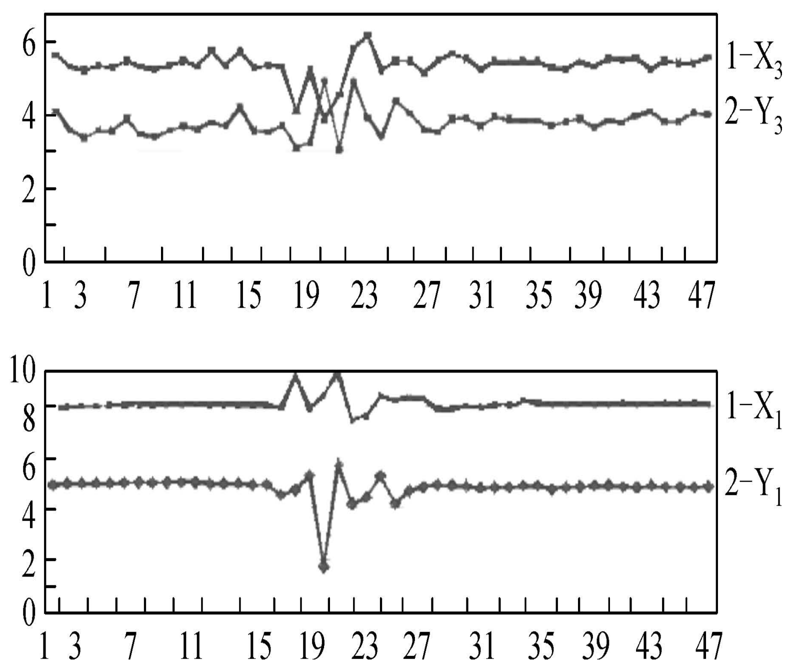
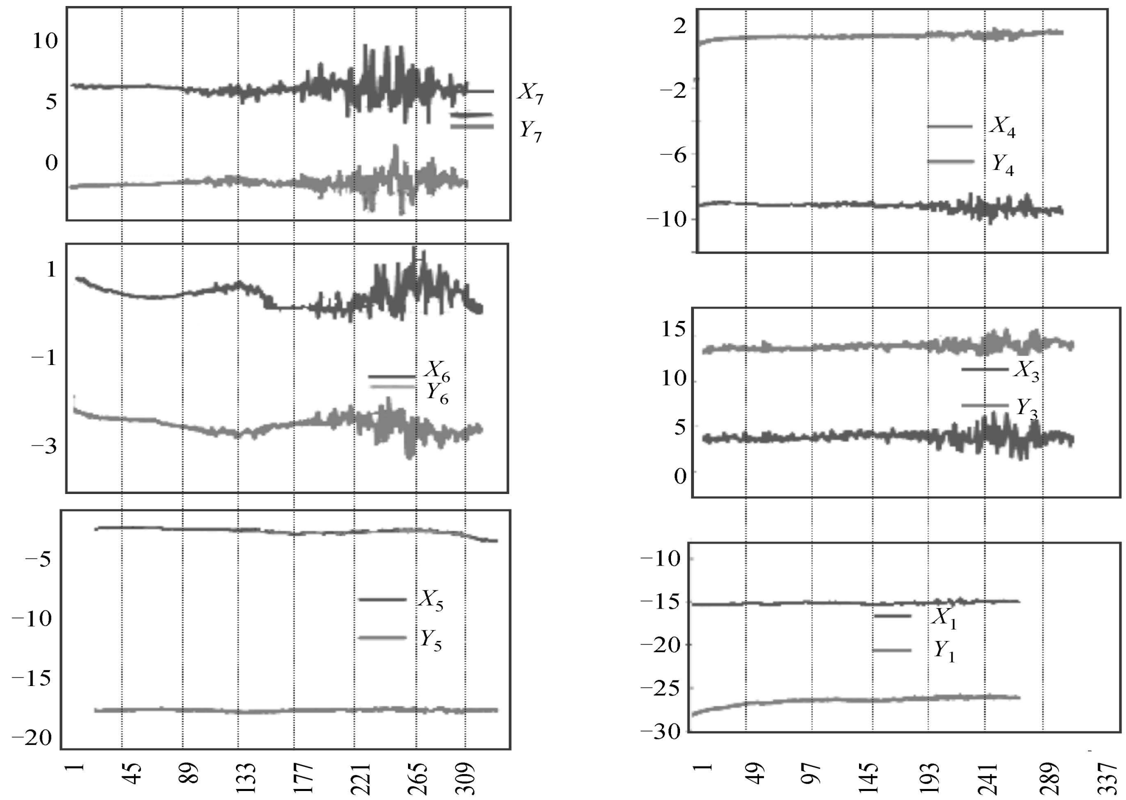
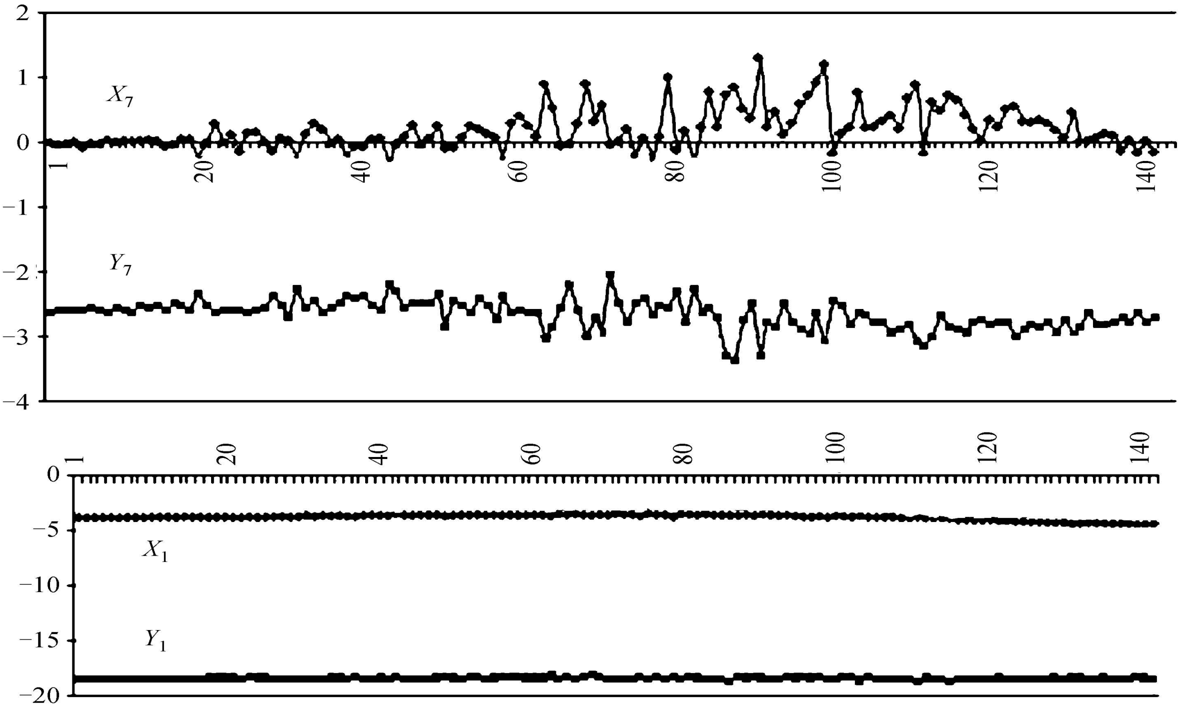


Fig. 13 Expanded record of tilts at Enguri dam to great Tohoku (Japan) EQ, M = 8.9 March 11, 2011, at 05:46:23 UTC on the stations 1 and 3, sample rate 1/10 min. Note maximal tilt (4 s) recorded at the X1 component



(a)



(b)

Fig. 14 (a) Example of wind-related perturbation in dam tilts (seiches): readings from 1 to 171 (arrow) correspond to calm weather and readings from 171 to 292 – to stormy one (see text for abbreviations); (b) Expanded record of tremor caused by lake water perturbations by wind (seiches) – mean period of perturbations of order of 30–40 min! File-Engurhesi-22.11.2010 (13.40.00)-24.11.2010 14.00.00), sample rate – 1/10 min

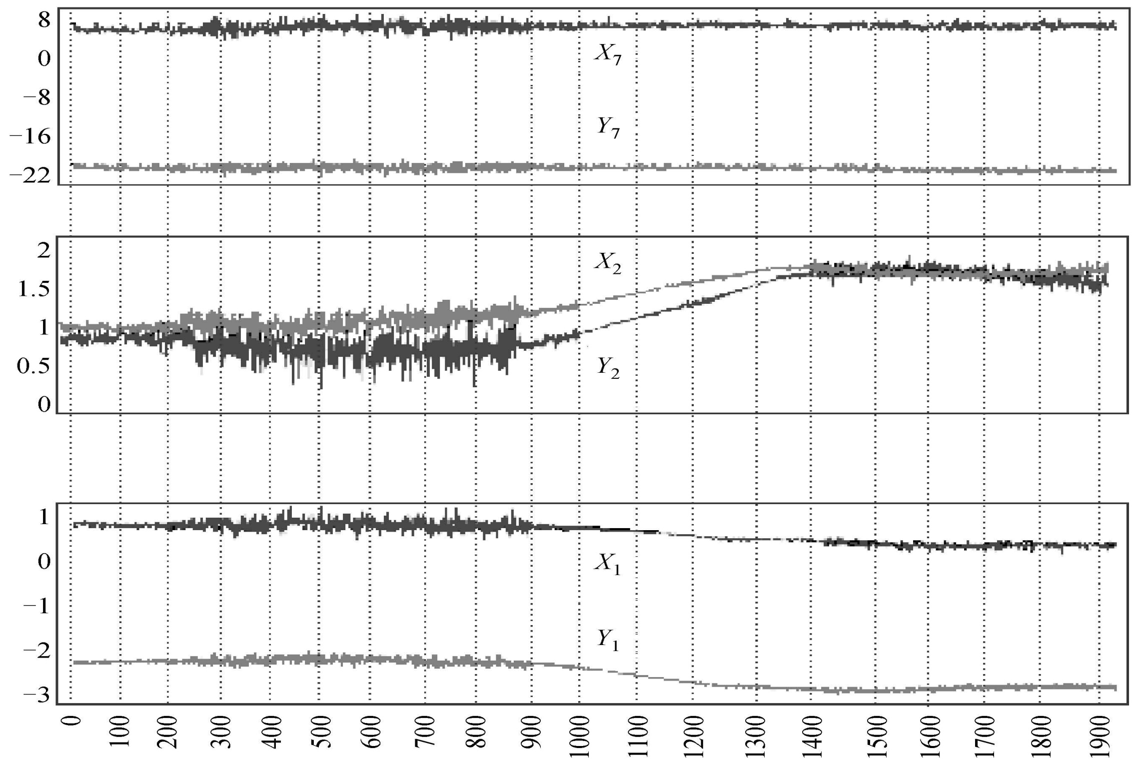


Fig. 15 Anomalous tilt tremors with relatively deep penetration (probably water discharge done 11-12 May 2010) at readings between 120 and 780. File: Engurhesi 11-12 May, sampling rate 1/min

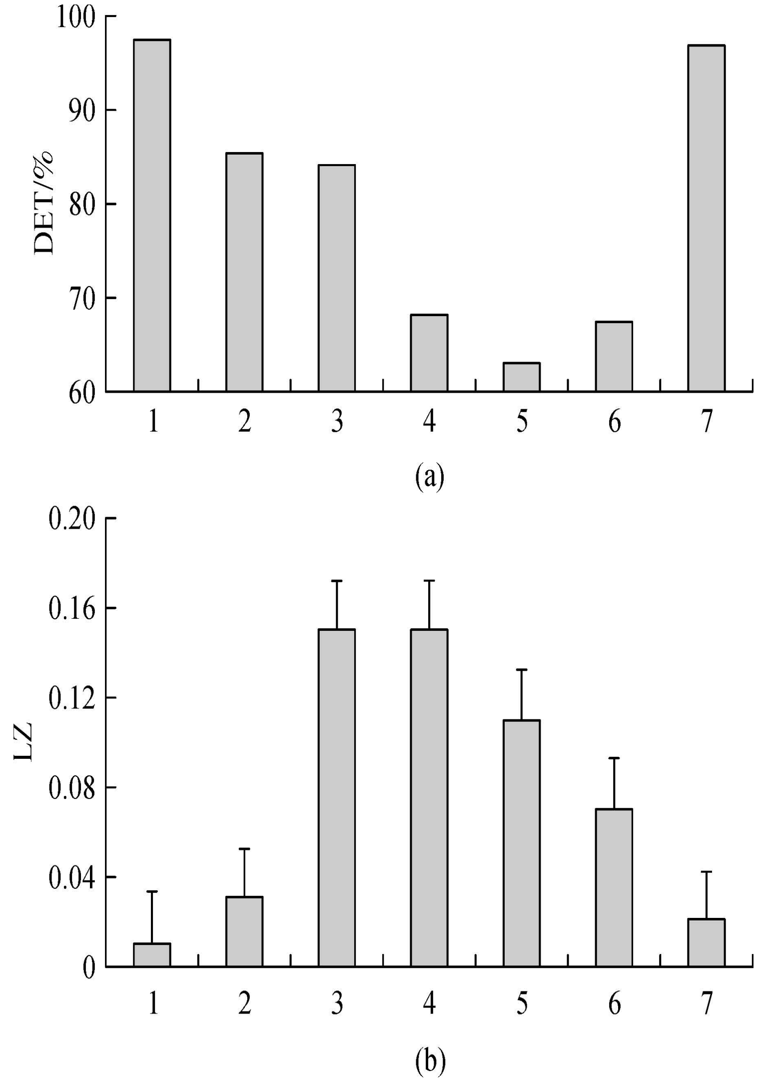


Fig. 16 (a) RQA determinism (%DET)measure calculated for Earth tilt data series for different stages of observation; (b) Lempel Ziv complexity measure calculated for Earth tilt data series for different stages of observation. Numbers on abscissa correspond to periods of observation

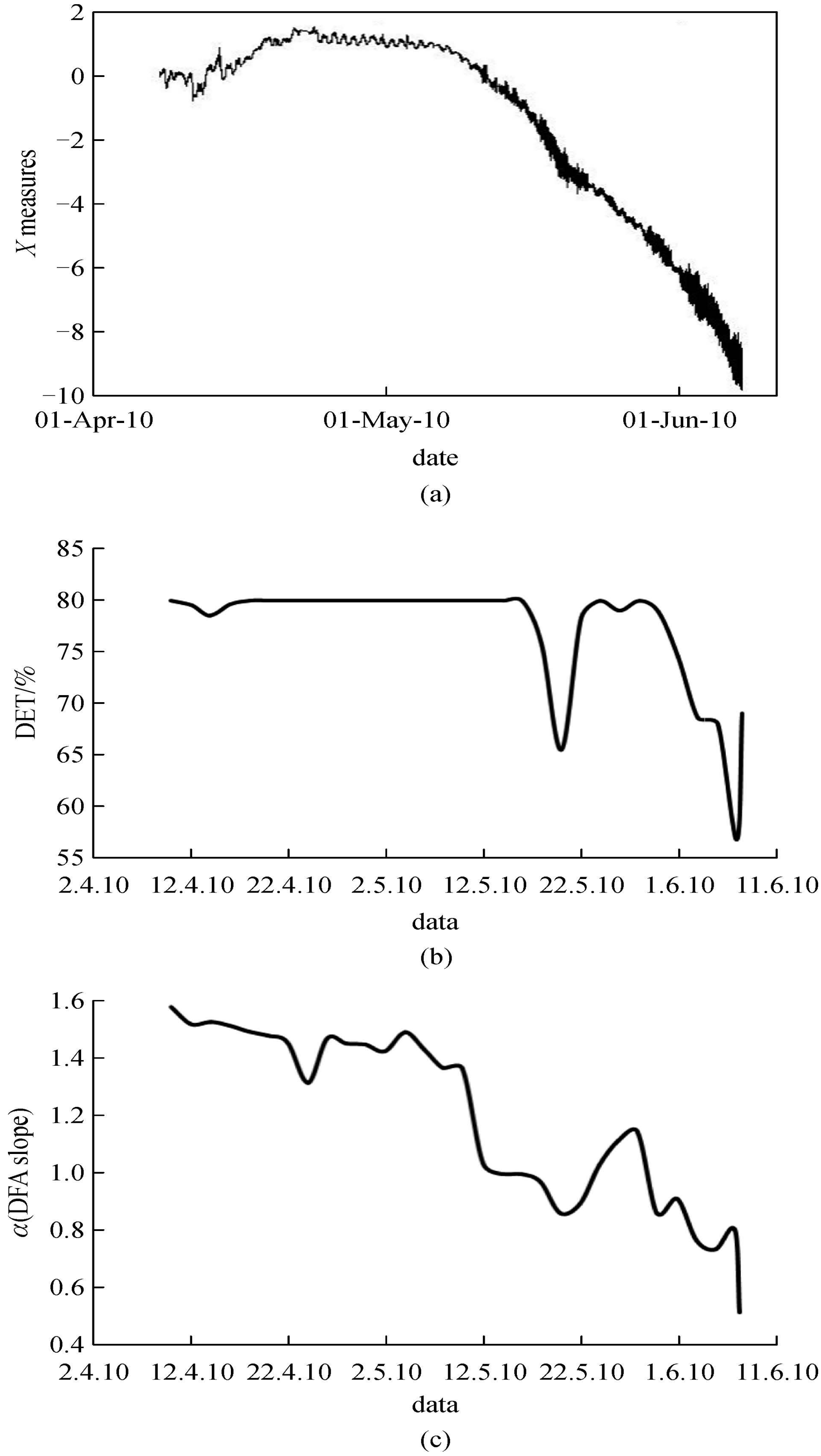


Fig. 17 Results of calculations by DAMTOOL using Detrended Fluctuation analysis or DFA and Recurrence Quantification Analysis or RQA (%DET -% of determinism) for the tilt time series from April 2010 to June 2010. (a) Original tilt time series;
(b) RQA%DET (% of determinism); (c) exponent α or slope of straight line fit in DFA. Note high values of spectral slope (DFA) and DET during regular regime, which point to highly correlated regime and strong deviations due to geotechnical impact – addition of high frequency component due to intensive discharge of water through dam outlet in 12.05–22.05.2010 and 01.06–11.06.2010 time intervals

Table 1 Comparison of observed plumbline horizontal displacements [16] and corresponding tiltmeters data (horizontal displacements in mm and tilts in seconds (in brackets with standard deviation) at maximal water level in the lake (510 m) for three sections of Enguri HPP [9] with theoretical (critical) admissible values of plumblines calculated by [15].

water level m	section 12			section 18			section 26		
	observed plumbline data mm	observed tiltmeter data mm (s)	critical admissible values mm (s)	observed plumbline data mm	observed tiltmeter data mm (s)	critical admissible values mm	observed plumbline data mm	observed tiltmeter data mm (s)	critical admissible values mm
360	20	11 (38±5.1)”	89 (122)”	35			15	14 (46±5.6)”	88
402	40	32 (63±4.5)”	59 (112)”	60	55 (70±3.9)”	55	30	37 (74±4.1)’	58
475	60	48 (56±8.7)”	31 (182)”	65			55	42 (55±5.5)”	26