

## REMOTE MONITORING SYSTEM OF THE BEHAVIOR OF THE NEW KORINTHOS ISTHMUS RAILWAY BRIDGE

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### ABSTRACT

The new double-track railway bridge crossing Korinthos Isthmus Channel was constructed with high specifications in the period from September 2002 to April 2004 by the Contractor assigned to the project by ERGOSE S.A. The bridge is of special interest both to the construction community involved in major structures and to the scientific world, because of the special project location characteristics, namely the underlying Korinthos Channel and the tectonic activity of the area, as well as due to the fact that this is the first partially seismically isolated bridge to be constructed in Greece. The long-term monitoring of the bridge's static and dynamic behavior, as well as its surroundings, was part of the construction design and was also improved in a subsequent contract to ensure the safe operation of the railway corridor, the performance assessment of its anti-seismic construction and the identification of any risk or failures in case of seismic activity. Monitoring sensors were selected on the basis of the need to perform unsupervised telemetric monitoring in order to continuously record and assess data; the objective was on one hand to establish direct communication with the equipment, to control recordings and operational status, and on the other to create a series of records that will show the behavior of the bridge over time. The system was commissioned in early April 2007 and it is undergoing continuous improvement through everyday trials. This paper gives a general presentation of this very recent system and provides initially measurements taken.

Keywords: New Railway Bridge of Korinthos Isthmus, Monitoring, ERGOSE S.A.

### INTRODUCTION

The said bridge is of special interest both to the major constructions community and to the scientific world, because of the special project location characteristics, namely the underlying Korinthos Channel and the tectonic activity of the area, as well as due to the fact that this is the first partially seismically isolated bridge to be constructed in Greece. The bridge was constructed with the Cantilevering method, using two bridge-builder formworks simultaneously from both sides of the channel (Sterea Hellada & Peloponnesus), through a process that held the contractor's crews for 4 months suspended in the air, 52-57m from the Isthmus' sea level. The foundation was constructed in 4 deep shafts, 15-35 m deep, with a diameter of 6-7 m, and piers were anchored on their cap beams providing a moment at an angle with additional downstream pile-groups. The approximately 12.000 tons girder was placed on special bearings on its piers and abutments, with additional side absorbers as limiters of its horizontal movements on the abutments and giant steel restrainers of vertical

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movements. An absorption system of the longitudinal movements with large nitrogen-filled shock absorbers secures that these movements are limited within the allowable limits and oscillations. Bridge spans between abutment (A1) – pier (M1) – pier (M2) – abutment (A2) are 60m – 110m – 60m, the deck is 12,70 m wide and the box girder height ranges from 11 m to 5 m, as the bridge is arching over the Isthmus.

In April 2004 and later, the bridge was filled with ballast, and rails and special joint devices were installed for the safe passage of Suburban Railway trains, which started regular services a few months before the 2004 Athens Olympic Games.

The construction design of the new bridge contained a minimal monitoring system, providing for the installation of load cells installed perpendicularly to the girder's sides, at the location of the A1 abutment on the Sterea Hellada side of the bridge, with a view to determine, through changes in exerted pressures, any side movement of the bridge girder caused by failure of the active fault P4 running almost laterally to the overall construction. The said devices were fitted and the measurements were taken onsite using a Bluetooth-operating device transferring data to a pocket PC (Figures 1-5).

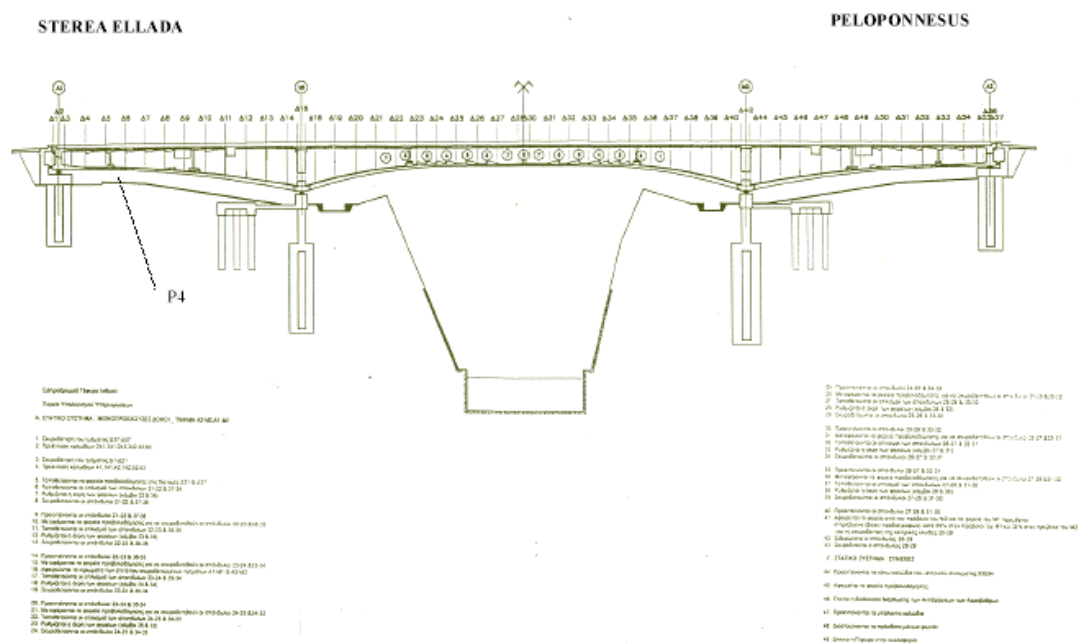
In a subsequent consideration of monitoring issues (2006), it was decided to specify a more complete monitoring system, which was integrated in a new contract and included the system's design, procurement, installation and commissioning. This system marked a new beginning in the application of new technologies by ERGOSE S.A. as regards monitoring of the state-of-the-art bridges constructed by the company. The objective was to have an overall supervision of the structure within its specific geotechnical and manmade environment, its influence therefrom (e.g. earthquakes, unpredictable external or internal events, slope movement problems of the Channel's steep corroded sides etc) and effects from the use of the structure itself (e.g. train passage, special loads developed on a case-by-case basis, etc).



**Figure 1. Greece - Korinthos Isthmus Channel between Sterea Hellada and Peloponnesus (new Athens-Patras railway corridor)**



**Figure 4. The bridge after completion (Summer 2004)**



**Figure 5. The bridge's longitudinal cross section with fault P4**



## THE GEOLOGICAL AND GEOTECHNICAL SITE OF THE BRIDGE

The final location of the New Railway Bridge of Isthmus Corinth was determined with the main criterion of achieving the most optimal possible Geotechnical environment, in the region's particular Geological field, that consists of the Neogene's deposits of North Peloponnese with the newer active tectonism (quite prone to tectonic movements due to the area's seismic activity).

Locations of most optimal stability of the already weathered channel slopes were sought out, the faults were mapped, the possible locations of wedge failures between the slipping zones were identified, and following an official confirmation from the competent public authorities that the channel will not be widened, the bridge foundation positions were horizontally identified.

Despite the slopes weathering, the regional Geology is clear from the channel profile (the slopes height -before excavations- in the bridge location is 55m from sea level). Both slope sides consist of Neogene layers deposits of shallow sea, a series with low dip, rich in fossils, with calcareous sandstones, calcareous and sandy marls, small-medium grain conglomerate-breccie-gritty sedimentations, thin beds of sand and clays with concentrated fossils.

There is practically no underground water, only drops or low humidity in few deposits were found which do not cause problems on rock stability.

The Tectonic of the region is new and active in a meaning that it is able to give movements across fault surfaces during or after strong earthquakes generated by the Alpian rock formations faults of the wider area.

There are chains of faults with small slipping surfaces and without large dimension parts that during the Quaternary had sporadically movements. Due to one such fault (P4), in SW direction and dip  $75^{\circ}$ - $80^{\circ}$ , the bridge foundations had to be placed on the two sides of this fault. The abutment A1 (Stereia Hellada) is placed in the upper part (NE) and the others (the centre piers M1 & M2 & abutment A2-Peloponnesus) in the lower part of the fault (SW). It is calculated that during the last years (including a strong earthquake in 1981 of 6.7 R), this fault has moved by 1cm.

The designer calculated that for the next 100 years, the total maximum tectonic movement could be up to 25 cm. The fault crosses the Isthmus channel and intersects the access road of the Peloponnesus piers with no further influence on the project foundation.

Because of the regional seismic-tectonic particularity, a specialised system of Seismic isolation is foreseen, as well as the installation of load cells fixed in the side bearings (dampers) of the St. Hellada abutment to record fault movements (P4) through load measurements.

The Geomechanic properties of rock formations were satisfactory for the foundation of the bridge and often better than those expected by the laboratory tests. According to them, there was a general SPT refusal, apart from individual horizons of clayey marl with values  $SPT=26-30$  and compressive strength  $0,6-2 \text{ kg/cm}^2$  in a position of the shaft for the pier M1 (St. Hellada) and this is the reason why this shaft should be excavated, at last, to a depth of 30m. On both sides the sandstones and sandstone marls had a compressive strength ranging from 9 to 70  $\text{kg/cm}^2$ , whilst the small-medium grain conglomerate-breccie-gritty sedimentations had values ranging from 5 to 16  $\text{kg/cm}^2$ . In general, due to the fact that in Stereia Hellada sandstone layers prevail, whereas in Peloponnese marly layers prevail, the indexes are relatively higher in Stereia Hellada. The following values were accepted by the design: Neogene formations of Stereia Hellada: Strength=3,5MPa, modulus of elasticity  $E=400\text{MPa}$ , Poison ratio=0,25 and Peloponnesus Neogene formations: Strength=2,0MPa, modulus of elasticity  $E=250\text{MPa}$  and Poison ratio=0,25.

From the laboratory measurements for the shafts of the piers foundation the following resulted (Table 1):

**Table 1. Geotechnical values**

|                      | Shaft for pier of Sterea M1 | Shaft for pier of Peloponnesus M2 |
|----------------------|-----------------------------|-----------------------------------|
| Side friction (Mpa)  | 0,36                        | 0,22                              |
| Point strength (Mpa) | 3,8                         | 2,7                               |

According to the final design, the safe depth for the piers foundation through shafts of reinforced concrete resulted for the four shafts as following (Table 2):

**Table 2. Foundation shaft dimensions**

|                |                       |                  |
|----------------|-----------------------|------------------|
| Sterea Hellada | Abutment A1, diam.6m  | Pier M1, diam.6m |
|                | Depth 15m             | Depth 31m        |
| Peloponnesus   | Abutment A2, diam.6m. | Pier M2, diam.7m |
|                | Depth 18m             | Depth 35m        |

## THE MONITORING PACKET

The safe operation of the railway corridor as well as the monitoring of the special anti-seismic behavior of the bridge, in relation to the particular geological, geotechnical and morphology of the bridge environment that has been modified by human intervention (construction of the Canal in 1893 and newer interventions), make the monitoring of the bridge essential for the prevention of failures.

For the monitoring of the whole construction from applications of rail loads as well as from external causes, the following monitoring instrumentation was installed between September-December 2006, which form a continuous monitoring system, one of the most modern in the world.

**Permanent Inclinometers (In-place inclinometers).** These are electronic devices permanently installed at pre-determined distance in vertical boreholes using properly oriented inclinometer casing. Three such permanent inclinometer strings were installed; one each near the edge of the Channel slope (one on the Sterea Hellada side and the other on the Peloponnesus side) so that a possible failure of the Channel slopes can be monitored over deep boreholes (35m); the third string was placed over the local geological fault P4 (a fault that crosses the structure transversely) so that a possible fault failure can be recorded as well as possible micro-movements possibly caused by secondary seismic excitation. These permanent inclinometer strings can record biaxial movements (X-Y) and store the measurements in the memory of an automating Data Logging unit installed on a mast above the borehole. The data is transmitted by a wireless modem at pre-determined intervals to the central Computer installed in the Terminal Monitoring Station that is located near the Sterea Hellada abutment .(Figures 6-7).



**Figure 6. Inclinometers with Data Loggers**



**Figure 7. Inclinometers in Isthmus slopes**

**Triangulation points.** In addition to the electronic monitoring of the area underground movements, triangulation points are installed at selected positions on the ground so that possible ground movements of the areas next to the fault P4 can be monitored by an ordinary topographical team.

**Triaxial Accelerometers.** Triaxial accelerometers have been installed monitoring seismic acceleration in three axes (X-Y-Z) so that the result of the seismic isolation of the bridge in relation to the bridge parts founded in the ground can be monitored. These sensors have a range of  $\pm 2g$  and have been programmed to trigger after a pre-set acceleration level (which will be modified by continuous evaluation of the system response) so that ambient noise-caused triggers can be avoided. Nine (9) such accelerometers have been installed for comparison purposes; one above the foundation of each pier/abutment and before the seismic isolation (4 pieces); one exactly above the previous, positioned on the bridge deck (4 pieces) and the last on the middle of bridge mid span, on the deck. Each accelerometer is combined with a local data logging unit and a wireless transceiver module. These units are powered by an internal battery recharged by a solar panel. The accelerometer possible movements are continuously transmitted to Central Base Station and through an array of aerials data is sent to the PC. The data is continuously evaluated by the software and, depending on the settings, an event is stored, if triggered. The recording is dynamic (Figures 8-9).



**Figure 8. Accelerometer on deck with sun cells**



**Figure 9. Accelerometer on pier**

**Displacement Transducers.** The relative movement of the isolated bridge structure against that of the piers/abutments is recorded in three axes (longitudinal, transverse and vertical). One instrument (wire transducer) has been used for each direction. Two triaxial devices have been installed, one on each abutment in Sterea Hellada and Peloponnesus and two uniaxial (transverse) units, one at each pier. These transducers are considered to be very reliable as they are also used for controlling the position of the flaps on airplanes and they can operate in accelerations exceeding 2g. (Figures 10-11)



**Figure 10. Displacement (transverse) and side load cell**



**Figure 11. Displacements X-Y-Z directions**



**Side loading monitoring (Load Cells).** These were installed in the side perpendicular devices partially obstructing movements, at the location of A1 abutment, on Sterea Hellada, during the construction of the bridge in 2004 with a view to determine, through changes in exerted pressures, any side movement of the bridge girder caused by failure of the active fault P4 running almost laterally to the overall construction. Such failure could cause the bridge to move sideways and exert pressure on the sides. These load cells have been connected to the central Data Logging network of the bridge (Figure 11).

**Concrete mass thermometer.** A sensitive thermometer is installed in the concrete mass of the bridge above the pier on the Sterea Hellada side.

**Environmental thermometer.** A sensitive environmental thermometer is installed under the bridge on the Sterea Hellada side to monitor changes in the air temperature (Figure 12).



**Figure 12. Temperature sensor**

**Wind Speed and Direction monitoring.** In the middle of the bridge span, a station for monitoring wind speed and wind direction has been installed on the bridge side rails. (Figure 13)

Both parameters are recorded in the PC running in the Terminal Monitoring Station at the same intervals as the other sensors.



**Figure 13. Wind measurements, speed-direction**

**Terminal Monitoring Station.** The station is installed in a pre-fabricated office box 3.5X3.0m placed under the bridge for better protection, near the Sterea Hellada abutment. It has been mains powered and has a telephone line available that allows remote communication via modem. A PC is continuously running in the Station and collects, through suitable antennas, the data from all the data



loggers as well as from all wireless accelerometers on the bridge. Data is evaluated, processed and stored, depending on the settings set by the operator, by three software packages running simultaneously (Figures 14-15).



**Figure 14. Terminal monitoring station under bridge**



**Figure 15. Receiver antennas**

### **THE PROCEDURE OF TELEMETRIC MEASUREMENTS**

The telemetry system was fully commissioned by the experienced Greek company (NEOTEK) who designed, proposed and supplied the equipment, and the ERGOSE personnel was trained on the system operation at the beginning of April 2007.

Measurements can be downloaded, using a PC equipped with modem, from any place, using a telephone line, with the computer running continuously at the Terminal Station of the bridge. The notebook PC has all the required software in order to communicate and download all the recorded data (all sensor readings are taken and stored every 3 hours except the accelerometers that are continuously transmitting the data and events will be stored depending on the trigger levels).

The data from each Data Logger on each side of the Channel is transmitted every 3 hours wirelessly using high gain directional antennas installed with line-of-site direction.

In reality, all data recorded can be presented to the operator on his notebook in any graph information the operator selects and for any time duration the operator selects in a user-friendly presentation.

ERGOSE will be in close co-operation with the supplier's specialists for whatever period is required in order to make the operation of the system and processing and presentation of data clearer and more understandable.

Special software is also included in the ERGOSE procurement of the system. This software can be used by a special Technical or Scientific Consultant, if such is required, at a point of time when the data recorded is considered to need further processing and analysis.

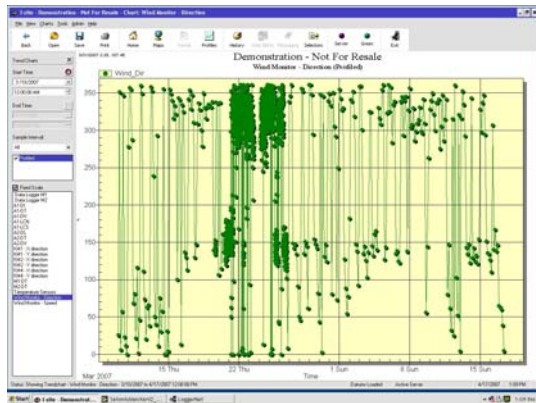
The indicative diagrams that follow are telemetrically received and cover the period from mid-March to mid-April when the present paper was written. (Figures 16 -25).

These graphs provide some initial first evaluations of the “innocent” behavior of the bridge showing the changes induced by the climatic temperature changes during the first ten days of April as well as of the momentary triggers taking place during the passage of a Suburban train, or changes on the wind etc. It is characteristic, for example, that with the increase of ambient temperature after April 5 we

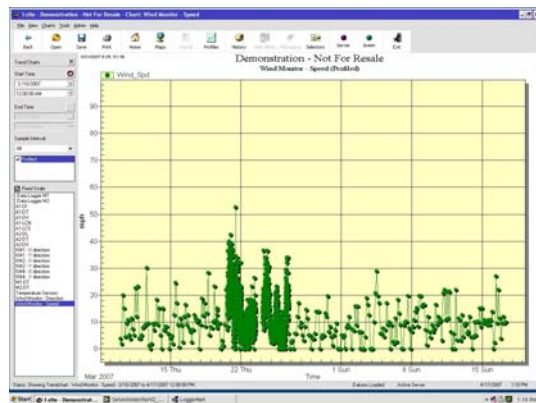
have some readings from the displacement transducers that indicate an “expanding” movement of the deck towards the Sterea Hellada abutment and to North East (n.b. the bridge is on a curved alignment) by 1-2mm and a lift of 2-3mm while, at the same time, the same movement is recorded as “moving away” from the Peloponnesus abutment. Another characteristic is, for example, that an event is recorded that exceeds the trigger level initially set for the accelerometers of Sterea Hellada and it is showing the moment the train is entering the bridge. In these cases, the triggering levels will be adjusted to a higher level.

Another, more “encyclopedic” observation is that 80% of the prevailing winds have a North-West or South-East direction and their speed reaches 40m/h.

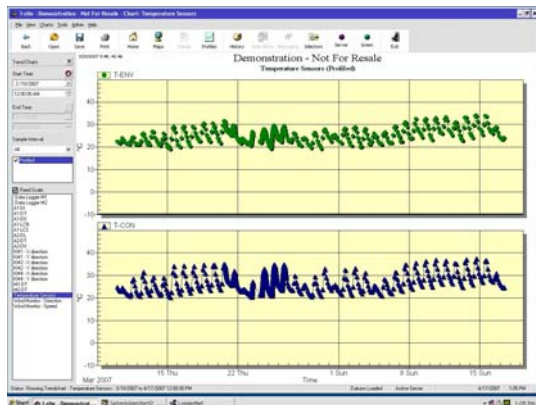
The graphs that follow (figures 16-25) are indicative to recently recorded measurements (until April 17, 2007).



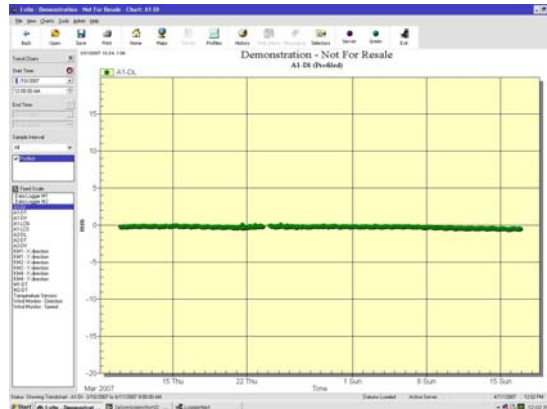
**Figure 16. Wind directions**



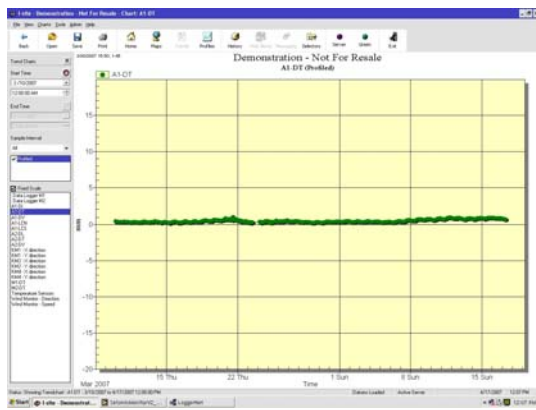
**Figure 17. Wind speed**



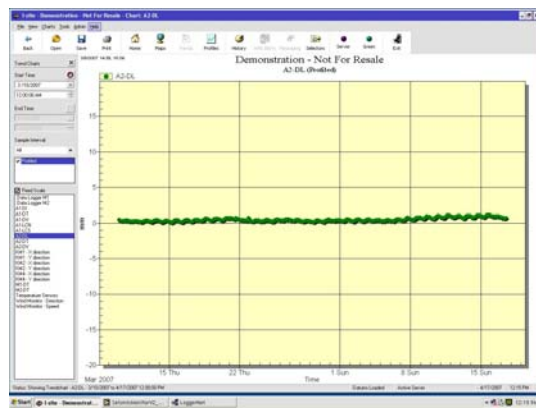
**Figure 18. Temperature sensors**



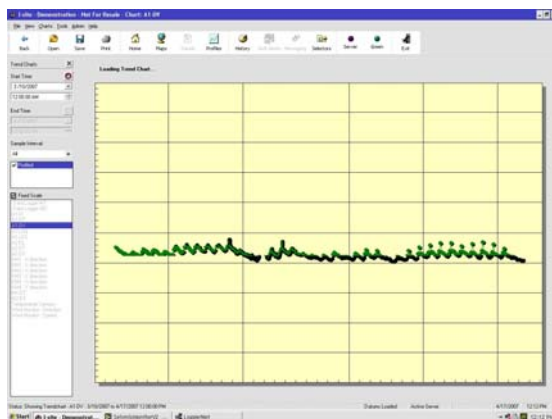
**Figure 19. Displacement of abutment A1(L)**



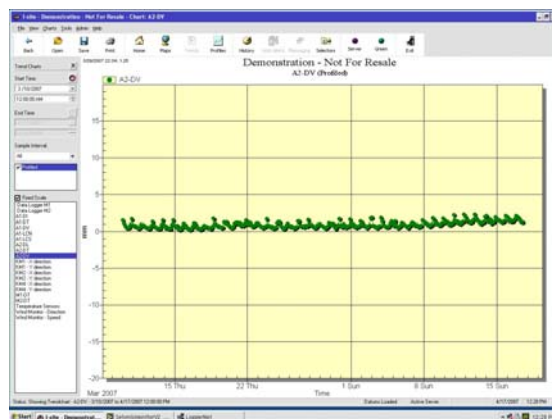
**Figure 20. Displacement of abutment A1(T)**



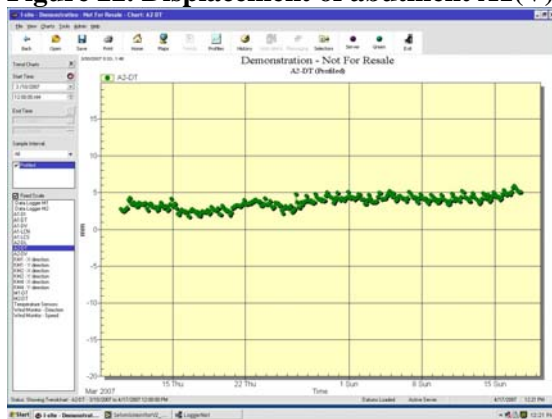
**Figure 21. Displacement of abutment A2(L)**



**Figure 22. Displacement of abutment A1(V)**



**Figure 23. Displacement of abutment A2(V)**

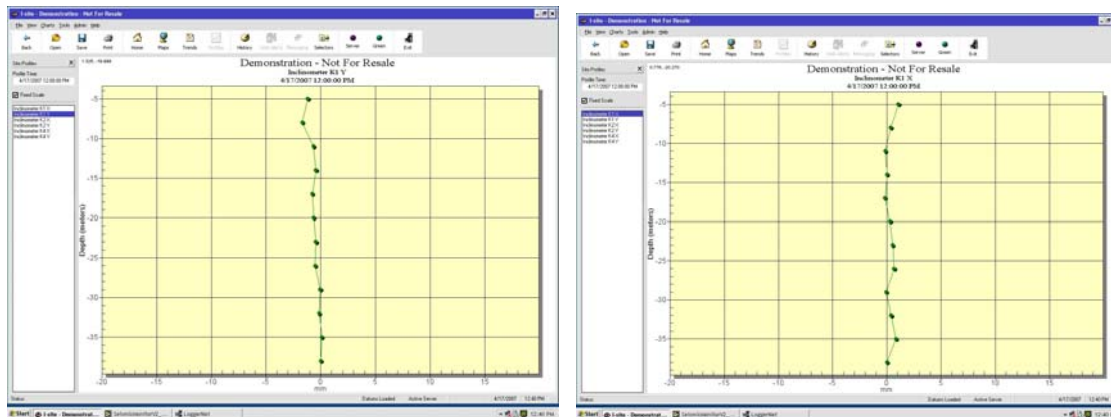


**Figure 24. Displacement of abutment A2(T)**



**Figure 25. Accelerometer dynamic measurements (T=transverse, L=longitudinal, V= vertical)**





**Figure 26. Inclinometer profiles**

## **CONCLUSIONS**

ERGOSE S.A. is a subsidiary company of the Hellenic Railways Organization (OSE) that manages the construction of the new high-speed railway network with the financial support of the European Union. Within the framework of this operational program, ERGOSE is vigilant in the search and application of new technologies, equivalent to a modern, fast and safe European railway. Under the same concept, a state-of-the-art vigilant telemetry monitoring system was designed and installed on the Korinthos Channel bridge in order to provide continuous information regarding the bridge and its surroundings. This system is operating as a pilot system, with a view to apply it in other construction projects along the new Greek railway network. This paper contains an initial presentation of the said monitoring system, with the disposal for more to follow, when adequate data packages become available individually or as a whole.

## **ACKNOWLEDGMENTS**

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