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TECTONIC STRUCTURE AS A POTENTIAL THREAT TO SAFE OPERATION OF THE PLANNED KAMIENIEC DAM

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ABSTRACT

The Kamieniec Dam will be constructed on the Nysa Klodzka River, in the Paczkow Graben situated close to the Sudetic Marginal Fault separating two major geological formations: the Sudety Massif and the Sudetic Foreland (SW Poland). The Tertiary graben has complicated tectonic structure characterized by a network of secondary faults dividing it into smaller blocks.

Geodynamic investigations, including analysis of repeated precise levelling measurements, have been undertaken to assess tectonic safety of the planned object. The results indicate present-day tectonic activity in the reservoir area. The analysis of levelling measurements shows differentiated vertical movements of separate tectonic blocks of up to ±(0.3-0.4) mm/year. Satellite GPS observations have proved horizontal movements of individual blocks inside the graben in the western (3 mm/year) and southern (1.5 mm/year) directions. The examined relevant geological and engineering documentations have given evidence of insufficient identification of the dam foundations.

The influence of the dam and reservoir on the surrounding ground and faults located about 250 to 350 m on the downstream side of the dam has been modelled with Finite Element Method (FEM). No direct interaction of the structure and nearby fault zone has been found.

The results of accomplished studies will act as the reference for future control measurements of the dam and its surroundings. The registered initial state of the ground will allow for reliable interpretation of deformation measurements of the planned dam in the cause-effect aspect.

KEYWORDS: embankment dam, geodynamic investigations, FEM modelling

1. INTRODUCTION

The mutual interaction between man-made water reservoirs and the surrounding ground causing deformations is well known (*Gupta, 1992*). To study and monitor this process special geodynamic investigations and numerical modelling of deformations should be performed (*Dluzewski & Gajewski 1994; Duffy et al, 2001*).

The Kamieniec reservoir to be located about 80 km south of Wroclaw (SW Poland) on the Nysa Klodzka River is one of the largest planned hydro-engineering projects in Poland. The main embankment dam will be 2 250 m long, 18 m high and 2.3×10^6 m^3 volume. Several side dams will also be constructed. The project is planned in two phases, first a dry reservoir and ultimately an over 100×10^6 m^3 volume lake.

The dam is planned within one of the most tectonically active areas in Poland, the Paczkow Graben, situated next to the Sudetic Marginal Fault separating the Sudety Massif and the Fore-Sudetic Block. Numerous publications point to the region's recent and present-day tectonic activity (*Cacon, 2001, Dyjor, 1993, Kontny, 2001, Oberc & Dyjor, 1968, Schenk et al, 2001*).

In the late 1999 research was started on the planned reservoir site with the intention to determine present-day activity of tectonic structures in this area and to assess the potential hazard to the dam structure. The studies consisted of field investigations, examination of geological and engineering documentations, geodynamic observations (satellite GPS and gravimetric measurements) and analysis of the results of repeated precise levelling measurements. The numerical modelling of reservoir-ground interaction with Finite Element Method (FEM) was also performed.

This paper presents results of geodynamic investigations (satellite GPS observations and precise levelling measurements) and the outcome of numerical analysis (FEM) of ground deformations caused by construction of the embankment dam.

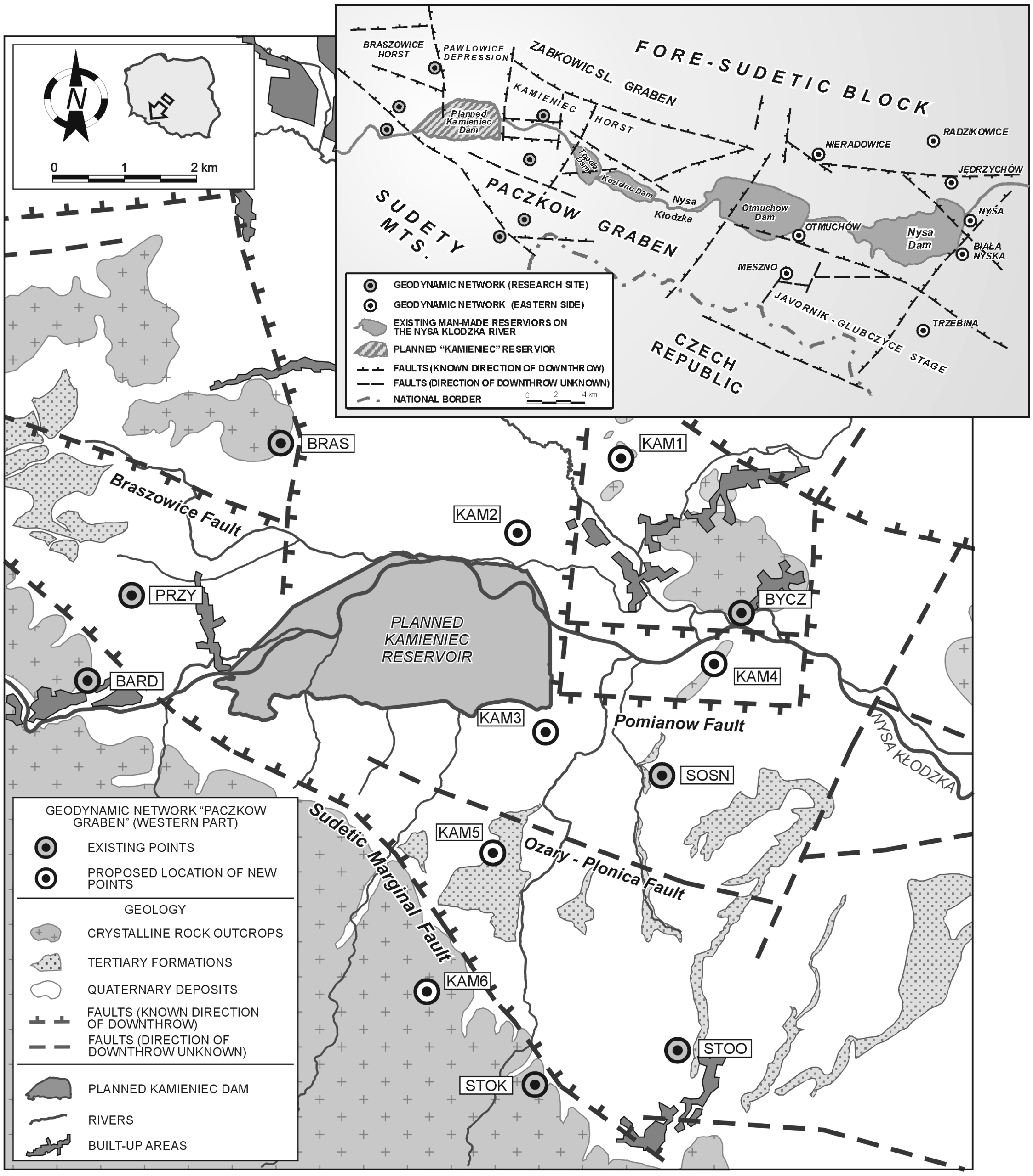

Fig. 1 Planned reservoir site with marked location of geodynamic network points and faults

2. CHARACTERISTICS OF THE RESEARCH AREA

The eastern part of the Fore-Sudetic Block and the Eastern Sudety Mts. have known history of tectonic activity documented by records of past earthquakes, e.g. Strzelin in 1895 (*Guterch & Lewandowska, 2002*). Other studies including e.g. morphological, geophysical and geodetic investigations (*Cacon, 2001, Dyjor, 1993, Kontny, 2001, Przybylski, 1998*) or the recent earthquake hazard map for Central Europe (*Schenk et al, 2001*) indicate that these are ongoing processes. The Paczkow Graben located on the border of two major geological units is considered to be one of the most tectonically active parts of Poland today.

The Kamieniec reservoir will fill most of the Pawlowice Depression located in the western part of the graben, characterised by complicated tectonic structure composed of numerous uplifted and lowered blocks divided by a system of secondary faults (Fig. 1 insert).

Analysis of the project documentation and geological data indicates existence of a network of faults on the dam's foreground, which include longitudinal fault running parallel to the main dam at a distance of approx. 250 to 350 m on its downstream side. The fault separates the Kamieniec Horst and the Pawlowice Depression and is buried under Quaternary deposits. Two parallel Pomianow faults of the southern stage of the Kamieniec Horst are located on the western side of the longitudinal fault (Fig. 1).

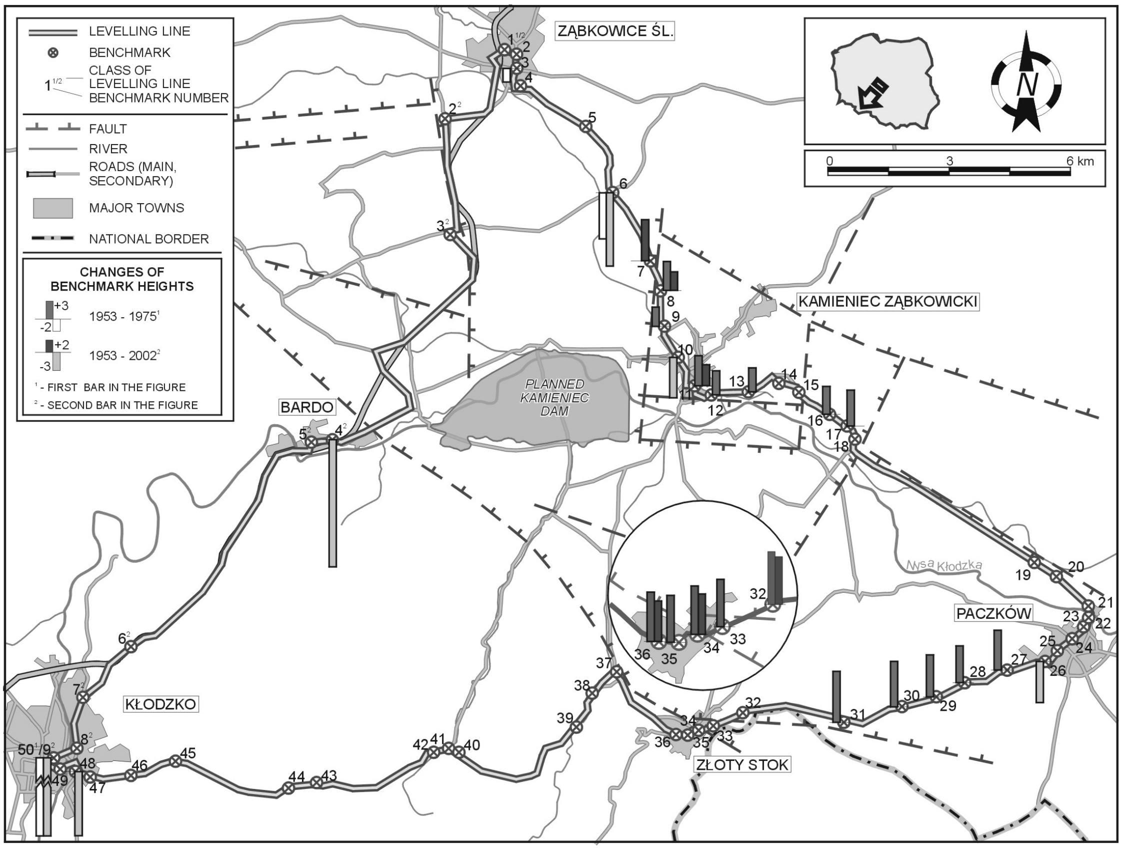

Fig. 2 National 1st and 2nd order precise levelling lines with shown values of benchmark height changes in the 1953-2002 period

Insufficient number of deep exploratory boreholes makes it impossible to determine if these faults extend under the dam, as could be concluded from descriptions of regional geology (*Oberc, 1972*). Certainly, this possibility must be taken into consideration during construction and operation of the dam. The embankment will be located on a layer of Quaternary complex of sands, loams and clays whose depth varies from several meters at the valley northern and southern slopes to approximately 35 m in the middle. This complex overlies a layer of much thicker Tertiary deposits, mostly clays with some loams separated by two layers of gravels and sands (Fig. 4). The detailed description of the research site's geology has been given by Blachowski & Cacon (*2003*).

In the early 1990'ties a 15-point geodynamic network "Paczkow Graben", shown on the insert in Fig. 1, was set up with the aim of regional geodynamic investigations (*Cacon, 2001*). Through the middle 1990'ties studies have been realised around the Nysa reservoir, located in the eastern part of the graben (Fig. 1 insert). The results have proved direct influence of that reservoir on the surrounding ground, which is thought to have activated a network of previously unknown faults located under the Nysa dam (*Cacon & Deeb, 1996*).

At the Kamieniec site 7 points (stations) of the "Paczkow Graben" network were used in the research, 4 of these: STOK, BARD, BRAS & BYCZ situated on crystalline rock outcrops and the remaining 3 in Quaternary formations stabilised at a depth of several meters (Fig. 1). All of the points have been stabilised with concrete pillars equipped with bolts for forced centring of measurement apparatus (*Cacon, 2001*). The network of 7 stations is designed in such a way that the research points are located around the planned reservoir site and correlated with main geological structures including ones outside the graben, i.e. points STOK and BARD in the Sudety Mts. (Fig. 1 & 3).

3. GEODYNAMIC INVESTIGATIONS

As has been mentioned above, geodynamic studies realized at the planned dam site consisted of satellite GPS and gravimetric observations. Both performed on 7 available points of the "Paczkow Graben" geodynamic network. The analysis of available gravimetric data (*Barlik & Olszak, 2002*) spanning a 10-year period of observations (1993-2002) has been described by Blachowski and Cacon (*2003*). It is worthy to mention here that during this time all stations showed decrease of the gravitational

Table 1 Characteristics of available precise levelling data

LEVELLING LINE	LINE CLASS	LENGTH OF LINE	YEAR OF MEASUREMENT	MEASUREMENT ERROR
Zabkowice Sl. – Kamieniec Zabk. – Paczkow	1	27.5 km	1953, 1975, 1999	m_0 = 0.4mm/km ('53) m_0 = 0.3 mm/km ('75) m_0 = 0.3 mm/km ('99) m_0 = 0.2 mm/km ('02)
Paczkow – Zloty Stok – Klodzko	1	33 km	1953, 1975, 2002	
Zabkowice Sl. – Bardo – Klodzko*	2	29 km	1956, 1989	-

acceleration and the fall has been significantly lower within the graben than in the geological structures surrounding it.

In this paper the results of satellite GPS observations and analyses of repeated precise levelling measurements are given only.

3.1. VERTICAL MOVEMENTS FROM LEVELLING MEASUREMENTS

There are three levelling lines passing through the research area (Fig. 2). Two national 1st order levelling line sections extending from Zabkowice Sl. through Kamieniec Zabk. to Paczkow and from Klodzko through Zloty Stok to Paczkow, as well as a 2nd order line running longitudinally from Zabkowice Sl. through Bardo to Klodzko. Together these form a triangle with the planned reservoir site inside it. The levelling lines extend over major tectonic structures in the area (Fig. 2).

The national levelling lines (1st order) were measured for the first time after the World War II in 1953 and then at about 20-year intervals in 1975 and in stages in 1999 and 2002. In case of the 2nd order lines the measurements took place in 1956 and 1989 with only 8 benchmarks re-measured in both epochs. The information characterising levelling campaigns is given in Table 1.

Archival records of field measurements have been used in the studies. For the purpose of geometric analysis of benchmark height changes a fixed reference level was chosen with the nodal benchmark in Zabkowice Sl. outside the graben boundaries serving as the reference. Relative benchmark height changes were calculated for the 1953-1975 and 1953-2002 periods in case of the 1st order lines and the 1956-1989 period for the 2nd order one. Subsequent correlation of the results with geological structure has yielded the following results, also shown in Fig. 2:

- Significant changes of benchmark heights in the fault zone separating the Pawlowice Depression from the Kamieniec Horst from +0.4 mm/year on the horst side to –0.3 mm/year on the other one in both considered time intervals,
- Elevation of benchmarks in the Zloty Stok Fault (benchmarks 27-32) and the Sudetic Marginal Fault (benchmarks 32-36) zones between 1953 and 1975 up to +0.4 mm/year, no continuation of this trend was detected for the second period (1975-2002), in Fig. 2 changes between 1953 and 2002 are shown,
- Subsidence of benchmarks west of Paczkow inside the graben in the area of thickest Cainozoic deposits.

In all the cases significant change of benchmark height means values greater than double RMS error of their estimation. The vertical movement experienced by benchmarks located in the city of Klodzko (outside the research area) is probably associated with the activity of man and is not discussed here. More comment on the results of these analyses can be found in Blachowski & Cacon (*2003*).

3.2. RESULTS OF SATELLITE GPS OBSERVATIONS

During the 4-year period of investigations two GPS campaigns financed from State Committee for Scientific Research grant were realised in 2001 and 2002. Together with the results of 1998 measurement that were made available (*Cacon, 2001*) these have been used to determine spatial movements of the research points in western part of the Paczkow Graben. In the paper only horizontal component is discussed. The parameters of GPS observations are given in Table 2. All of the campaigns were realised with static GPS technique. In 1998 the stations were measured for up to 8 hours (*Cacon, 2001*). Field data has been processed with BERNESE software at the Department of Geodesy and Photogrammetry of the Wroclaw Agricultural University (*Bosy & Kontny, 2002*).

The comparison of the results of epoch observations shows movements of probable minor blocks inside the graben's structure identified as the recorded displacements of the research points between three consecutive measurement campaigns. The graphical representation of GPS observation results (1998-2002) is shown in Fig. 3 with the horizontal displacement values for 1998-2001 and 1998-2002 periods presented in Table 3. Significant values, greater than ±2mΔ, are marked in bold.

Table 2 Characteristics of GPS campaigns 2001 and 2002

Date	Receiver type (No of receivers)	Antenna type	Session length	Measurement interval	Elevation mask
12.09.2001	Trimble 4700 (3) Ashtech Z-Xtreme (4)	TRM33429.00 with GP* ASH701975.01A with GP	10 h	15 s	10°
12-13.09.2002	Trimble 4700 (3) Ashtech Z-Xtreme (4)	TRM33429.00 with GP ASH701975.01A with GP	12 h 10 h	30 s	10°

* - ground plane

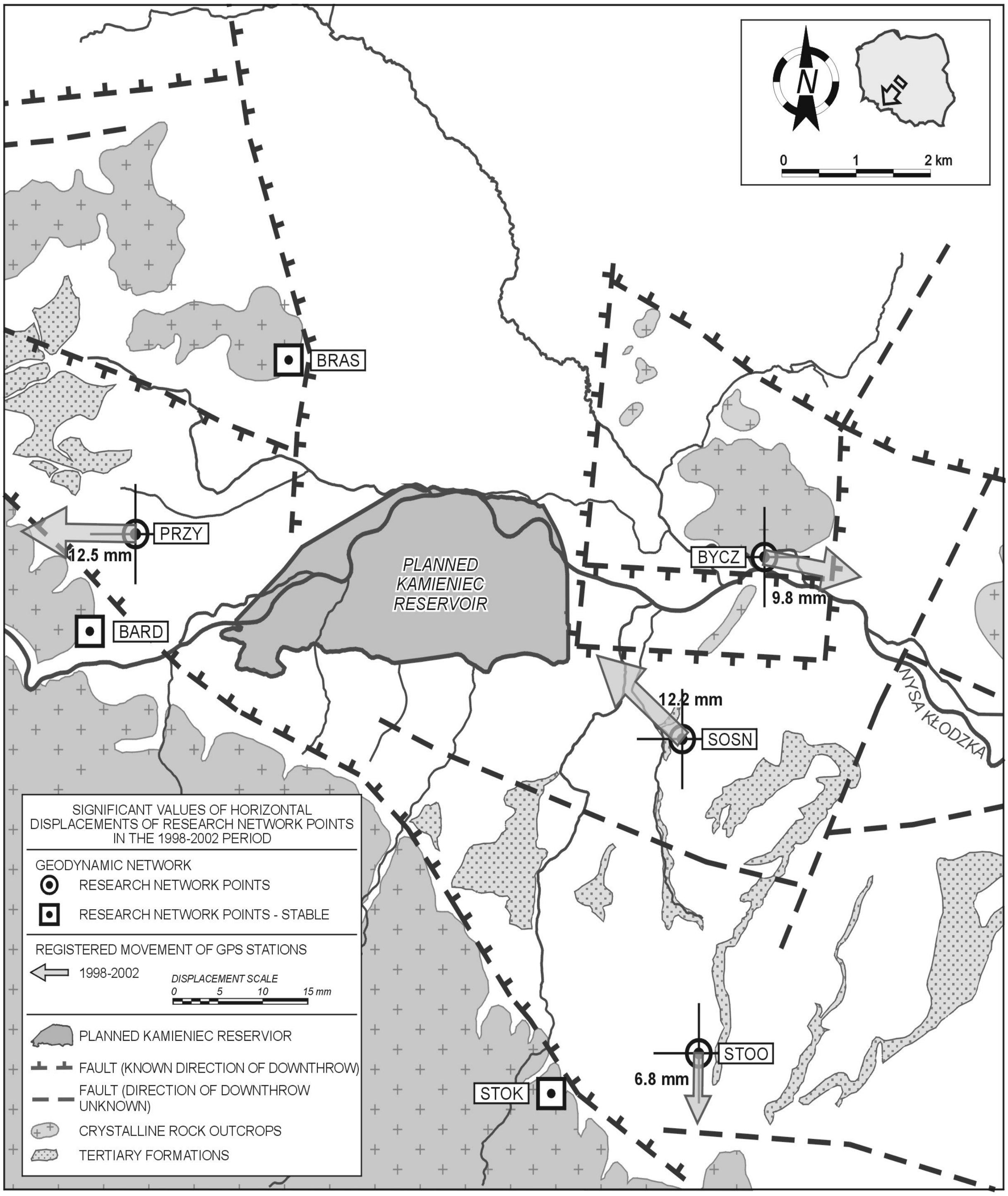

Fig. 3 Horizontal movement of research network points from satellite GPS observations between 1998 and 2002

Table 3 Horizontal displacement of the research points

No	POINT NAME	ΔXY [mm]	±mΔXY [mm]	AZ [°]	ΔXY [mm]	±mΔXY [mm]	AZ [°]
		1998-2001			1998-2002		
1	BARD	2.7	1.6	205.1	3.4	1.6	163.4
2	BRAS	2.0	1.5	41.9	3.1	1.6	12.2
3	BYCZ	**16.4**	1.8	51.3	**9.8**	1.8	109.8
4	PRZY	**14.4**	1.7	278.3	**12.5**	1.7	270.9
5	SOSN	**9.6**	1.7	272.3	**12.2**	1.7	308.0
6	STOK	1.0	1.4	325.5	2.3	1.6	288.3
7	STOO	**8.1**	1.6	210.9	**6.8**	1.7	193.7

Stations SOSN and PRZY located inside the graben move in the western direction at approx. 3 mm/year rate during the period of observations, while point STOO in the southern part of the graben shows movement (1.5 mm/year) towards south. The BYCZ station set up on crystalline rock outcrop within the Kamieniec Horst changes direction of movement from NE towards E in the successive epochs. The remaining points remained stable. The directions and values of displacements may suggest, earlier mentioned, subsidiary division of the graben's inner structure. However relatively short period of observations and just three GPS campaigns provide only the general information on the trend of movements that should be ascertained with future measurements.

3.3. LOCAL RESEARCH NETWORK "KAMIENIEC"

As a result of a thorough analysis of the dam and reservoir site with respect to the known geological and tectonic structure, an extension of the existing network, which has been set up for larger, regional investigations (*Cacon, 2001*) has been proposed. Six additional locations have been chosen around the reservoir and marked during field reconnaissance with autonomous GPS observations. Together these points form the local "Kamieniec" research network. The proposed geometrical configuration of the complete network (13 points), shown in Fig. 1, should serve two main purposes:

- investigations of geodynamic phenomena occurring in the ground around the reservoir area that could be measured with instrumental methods,
- network of reference points (benchmarks) for future deformation measurements of the dam.

New research points allow observations of geological units, which have not been included in preceding observations, e.g. point KAM 4 on the southern stage of the Kamieniec Horst (Fig. 1). Detailed characteristics of the project have been given in another paper by the author (*2003*).

4. RESERVOIR-GROUND INTERACTION WITH FEM MODELLING

Further work included modelling of the reservoir-ground interaction with the Finite Element Method (FEM). The intention was to determine possible influence of the dam on the neighbouring tectonic structures and the possible threat for the planned construction.

The advantage of numerical analysis with the use of FEM is that complicated geological conditions of the ground can be modelled in cases where analytical methods give only approximate results due to the assumed simplifications. One should keep in mind that a numerical model is still a generalisation of the real state of the ground and that the calculated deformation values must be regarded only as a reference.

4.1. FINITE ELEMENT METHOD ANALYSIS INPUT

The Finite Element Method due to limited space available will not be characterised here. Comprehensive description of the subject can be found in extensive literature e.g. in Zienkiewicz & Taylor (*2000*). In the research, available PHASES[2] software has been used for the numerical analysis (*Rocscience Inc, 2000*).

The calculation of deformations resulting from increasing load due to the dam construction and filling of the reservoir have been analysed for a 2-dimensional model of the ground. The following simplifications were assumed: no horizontal displacements in the dam's axis and isotropy of material. The relationship between stress and strain for all geological layers was approximated with a simple linear-elastic model. Two material parameters, in addition to bulk density, had to be defined: the Young's Modulus (E) and the Poisson's Ratio (ν). Material characteristics are given in Table 4. The values were selected from geological documentation (*PGPW, Hydrogeo, 1980*) to give maximum calculated displacements.

The deformations of the dam were not analysed in the model, as the aim of this study was to determine the maximum possible values of ground deformations.

Table 4 Material parameters used in calculations

MATERIAL	PARAMETER VALUE*		
	γ [kN/m^3]	E [MPa]	ν [-]
GRAVELS	16.0	67	0.25
SANDS	17.0	42	0.25
LOAMY SANDS	19.0	23	0.23
CLAYS	19.8	29	0.18
LOAMS	20.0	33	0.20
MICA SCHISTS	22.5	5 000	0.25
DAM MATERIAL	18.5	70	0.25

* - parameters taken from geological documentation (PGPW, Hydrogeo, 1980)

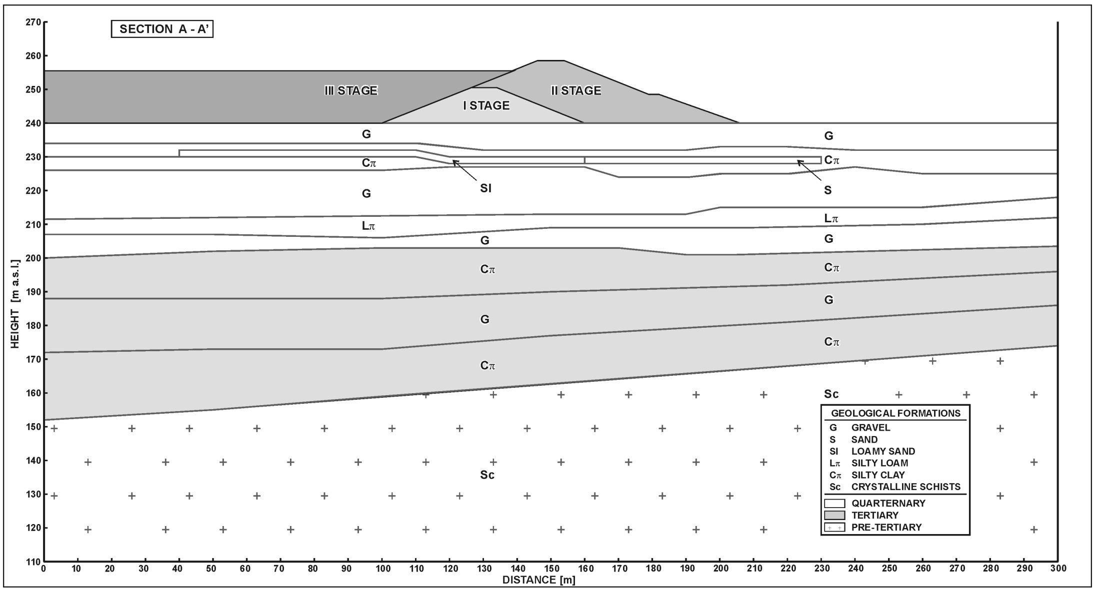

Fig. 4 Ground model of the dam foundations adopted for numerical simulation with PHASES^2 software with shown geological layers (cut here at 300 m for presentation purposes)

No consideration was given to changes in material properties due to consolidation and drainage. This paper deals with one representative cross-section through the dam foundation. The ground was modelled using 7 material types (Table 4). The section through the ground showing all geological layers is shown in Fig. 4. The FEM mesh and boundary conditions are presented in Fig 5. The problem included 2490 triangular elements with 6 degrees of freedom and 1326 nodes. The movement of the mesh nodes at the base of the model, 110 m a.s.l, in rock material, was constrained in both the vertical and horizontal directions. At the downstream and upstream ends of the mesh, the nodes were restrained in the horizontal direction. The model was extended beyond the toes of the dam, 350 m on its downstream side, which included the fault zone parallel to it (Fig. 1) and 100 m on the upstream side. In the Figures 4 to 7 the model is limited, due to presentation reasons, to a 100 m on the downstream side of the dam with the fault zone further 250 m away.

The analysis was performed for staged construction. The load was increased in three phases: the first included a dry reservoir, the second one a complete dam (18 m high) and the third stage, load increase due to filling of the reservoir (Fig. 5).

4.2. THE FINITE ELEMENT ANALYSIS RESULTS

The output of computer simulations was visualised as contours of the nodes' displacements. The values of ground settlements in all stages are given in Table 5.

Construction of the dry reservoir (stage I) causes little change in the ground. The greatest calculated increase of stress and horizontal and vertical displacements occurs in stage II. The maximum simulated stress values reach 0.26 MPa in stage II and increase to 0.30 MPa in stage III. The change of ground deformation values in stage III (filling of the reservoir) is relatively small compared to stage II (Table 5). The maximum vertical deformation occurs in the ground near the dam's axis at its foundation (Fig. 6).

Table 5 Maximum settlement of dam foundation in 3 stages

Maximum settlement values of dam foundation [m]		
Stage 1	Stage 2	Stage 3
0.16	0.34	0.39

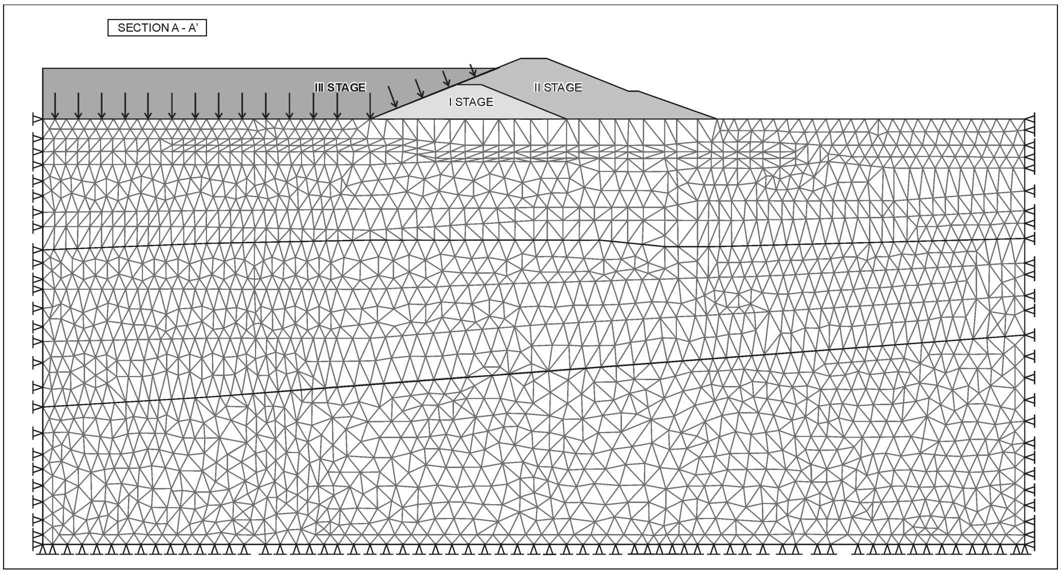

Fig. 5 Finite Element mesh and adopted boundary conditions

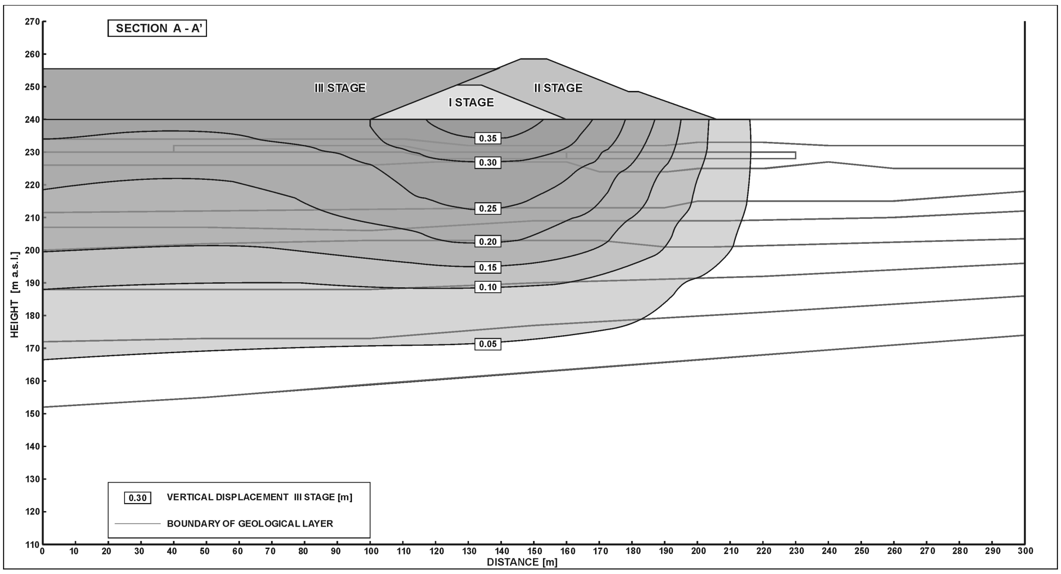

Fig. 6 Settlement contours in stage III

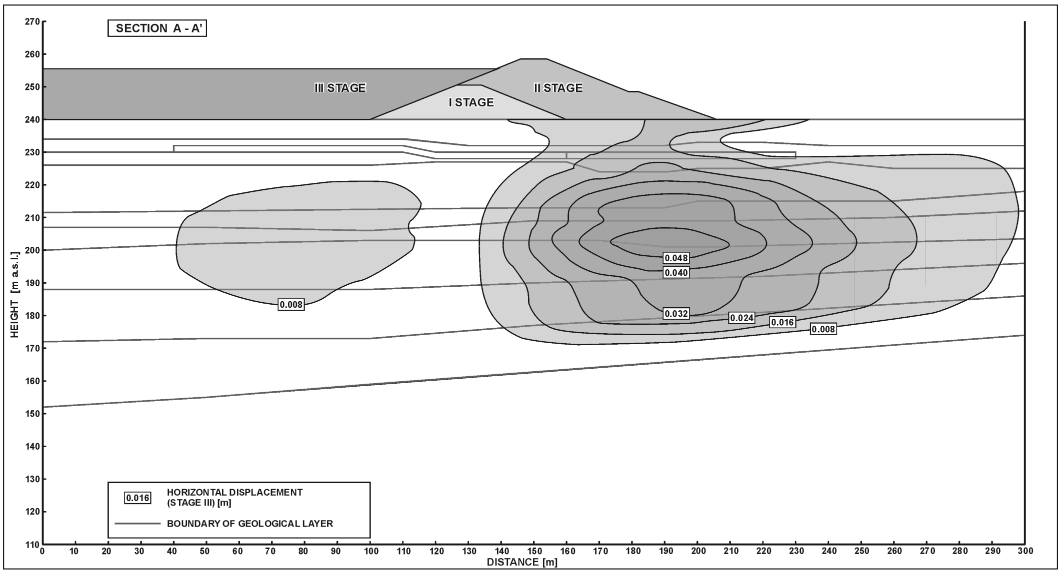

Fig. 7 Horizontal displacement contours in stage III

The predicted deformations in the ground on the downstream side of the dam are limited to the direct neighbourhood of the dam (Fig. 6 and 7) and are well short of the fault zone (not shown). The load imposed on the ground by the dam and water is relatively small due to the small size of the object and its effects disappear at a depth of approx. 170 m. a.s.l. Due to the reservoir's limited influence on the ground no further, more complicated analyses were performed at this point.

4.3. DISCUSSION OF THE RESULTS

The results should be regarded as frames of the possible changes only. The values obtained, particularly relatively high vertical displacements, result from the assumed simplifications of the model (described earlier) and the material parameters used (Table 4). No direct influence on the tectonic structure was found. However additional analyses of the Kamieniec Dam and reservoir should be performed if the existence of faults located under the dam (perpendicular to it) is confirmed by additional exploratory drillings and geophysical studies. The modelling should then comprise of predicting dam deformations through calculation of displacements at marked points on the crest and on the downstream face of the dam, which could be monitored with geodetic instruments during construction and use of the dam.

5. CONCLUSIONS

The results of geodynamic investigations: three precise levelling measurements (1953-2002), satellite GPS and gravimetric (not discussed in depth here) observations indicate present-day movements of the uppermost Earth's crust on the research site. These include:

- Significant vertical movements of benchmarks in levelling lines in several fault zones reaching up to ±(0.3-0.4) mm/year,
- Horizontal movements of research stations, measured with GPS, inside the graben varying between 1.5 to 3 mm/year pointing to its probable subdivision,
- General decrease of gravitational force, which is higher in structures surrounding the graben than within it.

These results prove that the area is still active today and are a good reason for further geodynamic investigations, particularly satellite GPS observations, on the dam site and suggest that the construction and operation stages of the future object should be closely monitored.

The possible causes of these movements are: endogenous tectonic processes, glacio-isostatic compensation or superposition of both these phenomena.

The predicted stress and displacement values are the result of assumed simple liner-elastic model and material parameters used and therefore should be regarded as a general reference only. The values and extent of reservoir-ground interaction generated with FEM modelling due to the load increase associated with dam construction and water impoundment are insufficient to raise tectonic activity of the neighbouring geological structures.

The extent of the studies realized on the Kamieniec site and described in this paper forms guidelines for the range of investigations to be realised prior to the construction and later during operation of the dam. This approach allows interpretation of the results of future control measurements of the object in the cause-effect. This aspect is generally overlooked during construction of embankment dams even in tectonic areas.

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