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MODEL AND FIELD STUDIES INTO THE DYNAMICS OF BLOCK SLOPE STRUCTURE FORMATION

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Abstract. The dynamics of block-type slope movements on travertine hills of Spiš Region in Eastern Slovakia have been studied by means of fissure monitoring and physical photoplastic models. A new interpretation of the investigated deformations is given. The models show the process in which different block structures of the marginal zones of the hills originate as the effect of inclination in the underlying beds of flysh st [illegible] toppling like that found at the eastern slope of Dreveník Hill or block towers slipping at their base while toppling inwards, like those at the opposite slopes of the same hill. Monitoring of [illegible] movements and/or data about stable hill sections showing present deformations in a phase of [illegible] long-term deformation process which can be studied in physical models successfully.

Keywords: block-type slope movements; ph [illegible] mations.

1. Introduction

Slope deformations [illegible] clayey [illegible] apt to sliding, notably under condition of high permeability of sandstone [illegible] During periods of abnormal rains pore pressure may increase in them due to water saturation to [illegible] process results in slope instability and catastrophic failures. This phenomenon is well known from Carpathian flysh and recent landslides after torrential rains of summer 1997 when precipitation sums reached 300 to 500 per cent of a long-term monthly average in the Vsetín region of Beskydy Mts. (Czech Republic) were very extensive and dan [illegible]

This type of failure struck superficial zones where flysh strata outcrop directly on slopes. However, flysh strata may show instability even in depth, buried permanently under the water [illegible] occur. Deformations [illegible] with relatively rigid blocks which overweight their plastic bedrock. This is the case of block-t [illegible] aside. It is especially the marginal [illegible] deformations due to instability in the underlying beds. Such deformations were described recently in general (Pašek & Košťák, 1977) as a phenomenon appearing in different areas in different situat [illegible] plastic bedrock.

2. Instability of Travertine Knobs

One of the most interesting examples of block type slope deformations in Central Europe is the area of travertine heaps or knobs in the center of Spiš Basin in Eastern Slovakia. The t [illegible] medieval Spiš Castle on the top of one of them, and the nearby Dreveník Hill as the second one. Researchers interested in block- [illegible] cracks in the old castle walls (Nemčok & Svatoš, 1974) with signs of separation movements which did not look like being a result of disintegration of elderly ruins only but rather being signs of travertine block slips in castle foundations. Those cracks were considered as the [illegible] occurred after the construction of the castle, which took place in the middle of the 13th century. The deformations then occurred obviously in the period of the last seven centuries. A question has been raised whether the deformation process stopped or not [illegible] seen in Fig. 1 which show the position of an outstanding block, the so called Perun Rock, with some medieval stonemasonry on its top.

Cross section through Dreveník Hill, a neighbour knob of the Spiš Castle (Fig. 2), shows the structure of the knob according to an older geological documentation. The scheme shows blocks slipping generally apart and downslope on ductile bedrock of flysh strata, inclined generally to W. According to the scheme, individual blocks rotate in the slipping process like cards [illegible] resting behind on both sides of the hill slopes.

Obviously, the geologist can make such a scheme of the cross section having general documentation of the surface with only indirect indicia of the situation in the depth. What is known is that numerous caves can be found under the blocks, and fissures between rock blocks are parallel with caves which indicates the deformation process due to instability in the bedrock. However, the mechanism of the deformation process could not be described in a more detail, and was estimated only. In fact, even some detailed field observations may differ from the above cross section of Fig. 2. On the photograph of Fig. 3 showing Dreveník Hill we can observe towers of travertine blocks in a little different configuration. The picture is taken at the eastern margin near the hill top where the flysh bedrock is dipping into the knob and rock blocks show inclined positions of the form of a fan. Their heads are toppling [illegible] inclinat [illegible] from dipping westward on the hilltop to dipping eastward on the slope. There is a regular increase in toppling of the block towers eastward [illegible] indicates a process of toppling in the block with stonemasonry on the top. [illegible] the toppling was explained by caving, since a cave has been detected underneath.

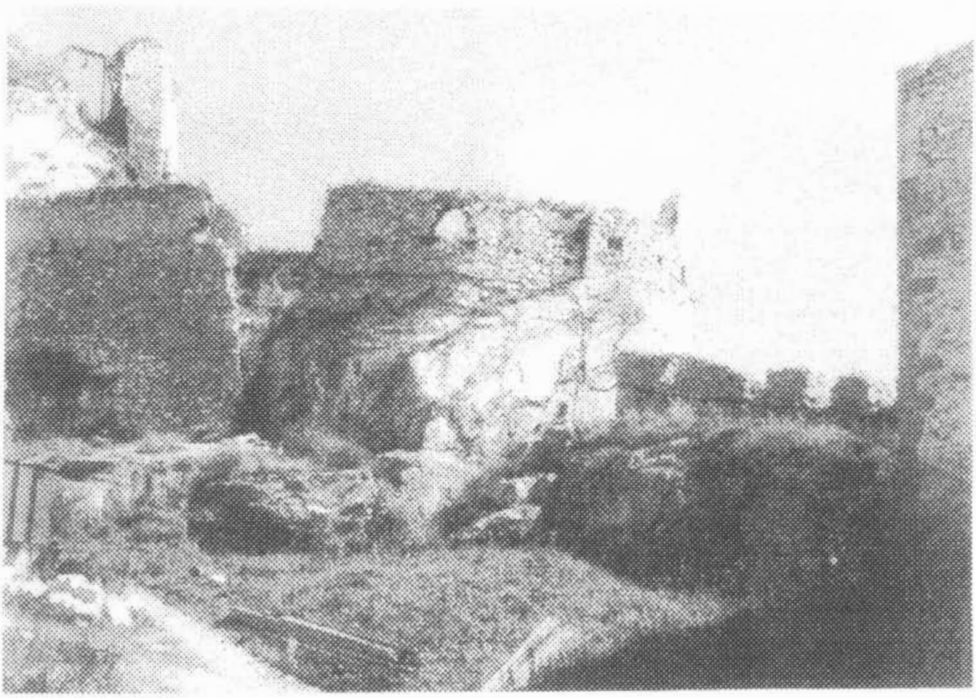


FIG. 1. The wall crack N of the main Spiš Castle gate which was supposed to evidence movements of travertine blocks in the castle foundations. The crack separates a huge block of travertine called Perun Rock (right) from a stonemasonry wall (left), and indicates opening, transversal displacement and rotation of the Perun Rock. The first point of movement monitoring.

Trhlina v obvodové hradní zdi severně od hlavní brány Spišského hradu. Trhlina odděluje mohutný blok travertinu nazývaný Perunova skála (vpravo) od kamenného zdiva (vlevo). Naznačuje rozevření, příčný prokluz a pootočení Perunovy skály
známkou, že travertinové bloky základů hradu nejsou stabilní. Zde byl osazen prvý bod kontrolního sledování pohybu P1.

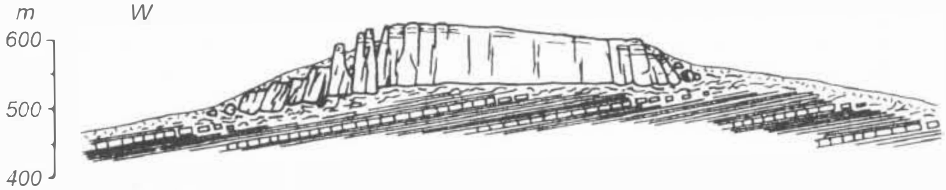


FIG. 2. Cross section through Dreveník Hill according to geological documentation given by Nemčok & Svatoš (1974)

Příčný řez Dreveníkem. (Podle Nemčok & Svatoš (1974).

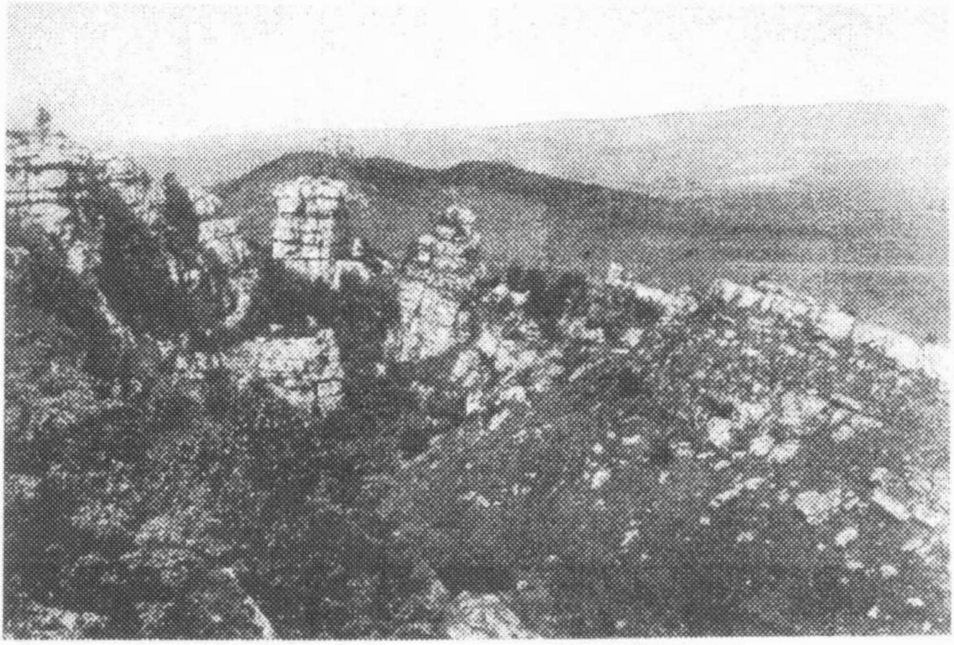


FIG. 3. View of travertine blocks in the eastern marginal zone of Dreveník Hill. Here
tion as if rotated with their heads progressively downslope
pr
tine knob in the neighborhood of Dreveník Hill is towering
in background on the second horizon.

Pohled na travertinové bloky na východním okraji Dreveníku. Bloky se staví v progresivních náklonech po svahu do formy vějíře. V sousedství Dreveníku se nachází další travertinové těleso se Spisským hradem. který je patrný v pozadí na druhém horizontu.

Such details depend on the internal mechanism of
the massif and may be important
evaluated. To understand better the process and conditions due to which it may
be evoked, there was a demand f
investigations. Therefore, several
among them, were instrumented to monitor potential movements between blocks
directly. Later, even a series of
movements, were produced.

3. BLOCK MOVEMENT MONITORING

Earlier
caves, and even evidence of gravitational def
caner

and even outlined the monitoring results of the deformation measurement on Spis, obtained in the introductory period of the monitoring organized in cooperation with the author of this work. Therefore, the description of details and det[illegible] drawings given by Fussgänger will not be repeated here. However [illegible] continued, and results of the prolonged period of measurement will be briefly given thereafter, with necessary information that follows.

Three points on cracks of the Spis Castle were selected for monitoring and instrumented in 1980. Crack gauges TM71 working on mechanical optical principle (moiré) were used as movement indicators (Košťák, 1991).

The instruments were installed on steel holders cemented into shallow boreholes in the opposite walls of the investigated cracks to indicate 3-D relative displacements between the two separated bodies. Resulting movements are therefore registered in three Cartesian coordinates representing crack opening or closing (x coordinate), horizontal shearing (y coordinate), and vert[illegible] crack (z coordinate). Orientation of the coordinates is individual at the particular points, with [illegible] opening due to slope movements.

First point [illegible] the zone of the eastern slope of Spis Cas[illegible]. [illegible] movement of Perun Roc[illegible]

Second point P2 has been ins[illegible] masonry of an open wall crack. The wall is oriented to WNW downslope, and represents a connection between the external fortification wall with the central travertine cliff. It is instrumented to monitor slope movement in for[illegible] with foundations on the slope [illegible] axially in the wall, i.e. downslope agai[illegible]

Third point P3 has been installed in the northern sector of the castle outside the fortification, instrumented to monitor relative movements between two high travertine blocks in the steepest slope of the Spis Castle Hill. In this case x axis is oriented unusually, [illegible] movements between the two blocks aside, while it is the y axis, which is oriented downslope, indicating shear in the fissure.

Later, in another phase of monitoring, other six points were instrumented. This phase started in 1992. Two points were located close to the point P1, *point TM1* above the Perun Rock, *point* [illegible] were located outside the fortifications, right on the hill slopes, intended to monitor individual travertine towers. However, the outside points had been demolished soon by local vandalism, so that it was impo[illegible] of several attempts to reconstruct the points. Till now, the main results come from the orig[illegible] even those measurements have been interrupted, points P1 and P3 demolished also, and point P2 removed during reconstruction works in 1994. In spite of such problems, interesting results have been obtained.

Points P1, TM1 and TM2 monitor [illegible] agrams of the displacements are in Figs 4, 5 and 6. The orientation of co-ordinates

in those
— fissure opening; $+y$ — sinistral movement in the fissure; $+z$ — vertical shear in the fissure, i.e. subsidence of the Perun Rock in respect of the outside blocks. One can see that co-ordinates in Figs 4 and 5 are parallel. It means that fissures above the Perun Rock open gradually with sinistral movements between their side walls. As for the co-ordinate z, it develops to negative values, which means displacements opposite to subsidence. Looking to Fig. 6, we may notice again sinistral movement in y, while opposite trends in x (fissure closing), and z (Perun Rock subsidence). Considering results from this three points with respect to the Perun Rock, we may conclude permanent tilting of it down the hill (opposite walls moving opposite vertically), and downslope shifts
change) with an additional subsidence of the Perun Rock (the lower fissure indicating more than twice the subsidence rate of the upper one). There is coincidence in P1 and TM1 in the fissure opening rate between 1992 and 1995 (about 2 mm per 3 years). There is also an indication of acceleration of the process in this period in all the three diagrams. The finding of the Perun Rock tilting coincides with the situation of the block in Fig. 1 thus proving that the process is active, continuing from the period of the castle construction.

Point P2 (Fig. 7) which monitors deformations in the western section of the castle, indicated serious dextral movements in the old stonemasonry crack, i.e. displacements of the external fortification wall to NNW. The movement is quite regular and reads about 1 mm per year with a simultaneous crack opening of about 0.30 mm and vertical shear of about 0.29 mm per year. In that the vertical shear is negative.
Such a finding is in a good agreement with Fussgänger's (1985) results, who had not more than three years of observations.

Point P3 (Fig. 8) installed in the northern sector of the castle between high towering blocks outside the fortification, has not indicated any trend of movement showing that this section of high blocks may be considered stable at present.

Other points have not shown clear results, either due to a short period of operation, or due to repeatable demolishing. Additional details were described separately (Vlčko et al., 1998). However, results from the Perun Rock on the eastern slope, as well as those from the western slope side confirmed the deformations as presently active.

4. MODELS OF BLOCK STRUCTURE DYNAMICS

To confirm the deformation process of the travertine disintegration and to gain an additional mechanical explanation of it, a series of model experiments has been performed. The models of this type were developed in our laboratory (Košťák, 1977; 1982). Such models can be useful to provide the insight into the mechanism of many different geological processes, having the ability to produce rheological deformations and finally even structures in real time, therefore to show dynamics of the process, and time development of the studied structures (Košťák & Zeman, 1982; 1990). Although Spiš Castle deformation monitoring started not earlier than

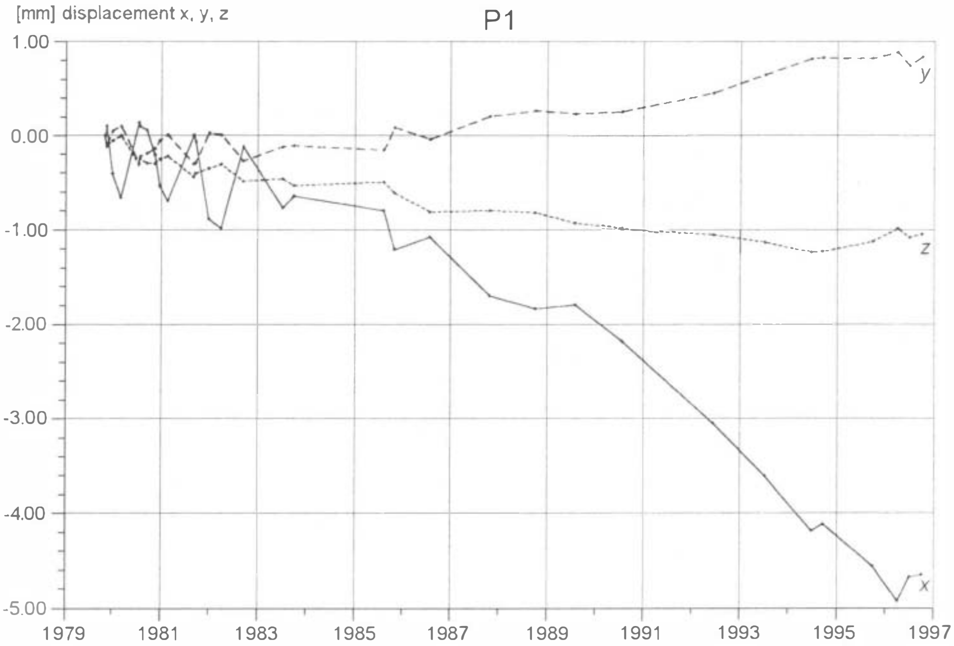


FIG. 4. Displacements recorded at the point P1, between the Perun Rock and the wall N of the main Spiš Castle gate shown in Fig. 1.
$+x$ — fissure opening; $+y$ — sinistral movement in the fissure; $+z$ — vertical shear in the fissure, i.e. subsidence of the Perun Rock in respect of the outside blocks. Years indicated at the end of intervals.

Posuny zaznamenané v bodě P1, mezi Perunovou skalou a zdivem severně od hlavní brány Spišského hradu (viz obr. 1).
$+x$ — rozšíření trhliny; $+y$ — levotočivý prokluz v trhlině; $+z$ — svislý smyk na trhlině, tj. pokles Perunovy skály relativně vůči okolí. Letopočty na konci intervalů.

in the year of 1979, with a prospect not to come to any definite results before a period of several years of repeated measurements, the first model experiments into the deformation of Dreveník type were finished and evaluated as early as in 1976, and then published (Košťák, 1982). The model of Dreveník deformation was provided there as an example of a successful application of such a model work.

The models use agar–agar gels of very low concentration in water as the main constituent. The hot solution is being poured into transparent vessels. After gelation in the vessel the material is ready to be studied under external loading conditions combined with the body weight of the gel itself. All kinds of different boundary conditions can be created. In the case of travertine heaps which represent layers sedimented on the top of slightly inclined flysh strata, the original situation can be

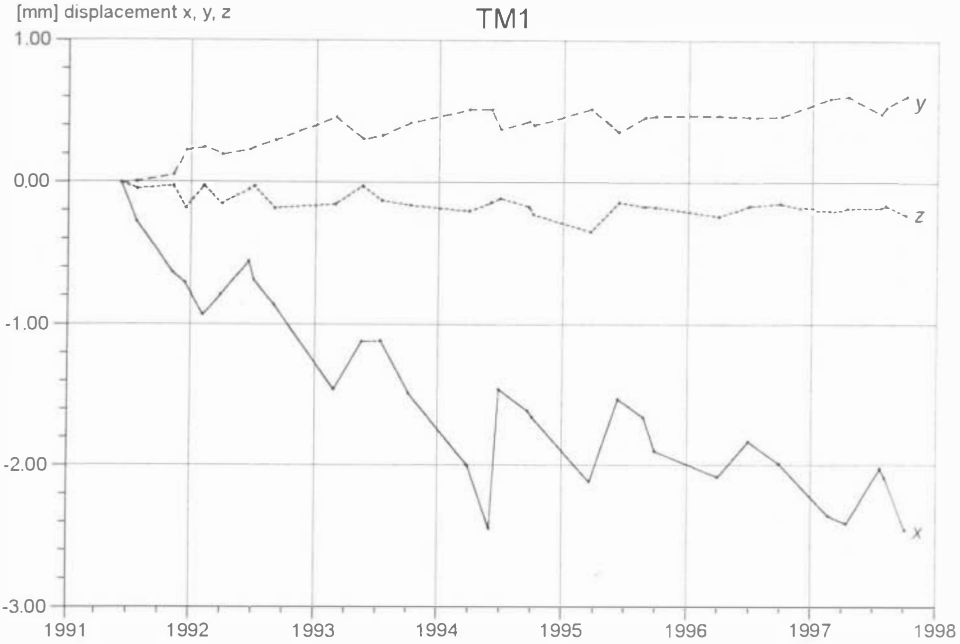


FIG. 5. Displacements recorded at the point TM1, i.e. in a frontal crack about 5 m distant from the point P1 at the Perun Rock (Fig. 1). Coordinates of the movements see Fig. 4.

Posuny zaznamenané v bodě TM1, tj. v čelní trhlině asi 5 m před bodem P1 u Perunovy skály (obr. 1). Souřadný systém jako v obr. 4.

supposed very simple — a homogeneous block with a free edge, loaded by model own weight, and sitting on a slightly inclined (5 to 10 deg) slippery bottom having enough time to deform. Because some predisposed superficial fracturing of the travertine could have been supposed, a row of rigid blocks had been lain on the model surface. The blocks increased the load being disposed to become heads of the towers that were supposed to develop in the model. As for the free edge, an edge partition in the vessel was slowly removed leaving the gel body free to expand and move out to a side. The opposite edge was left shut off providing internal conditions of the model body. In such a way a cross-sectional model of a heap was prepared. After producing the edge free boundary condition, the model was left to develop its structure. First, viscoplastic deformations started in the body spreading slowly towards the free edge and cracks started to propagate, leaving high tower-like bodies under the top rigid blocks, and toppling appeared.

Observations proceeded in polarized light. Due to optical sensitivity of the model material, stresses that developed in the model became observable by light colors while unloaded patches rest dark. The deformation process took several hours and was grasped by filming. Individual snaps of important phases are given in series of Figs 9a and 9b with time indication (hour : minute). Rigid blocks are not

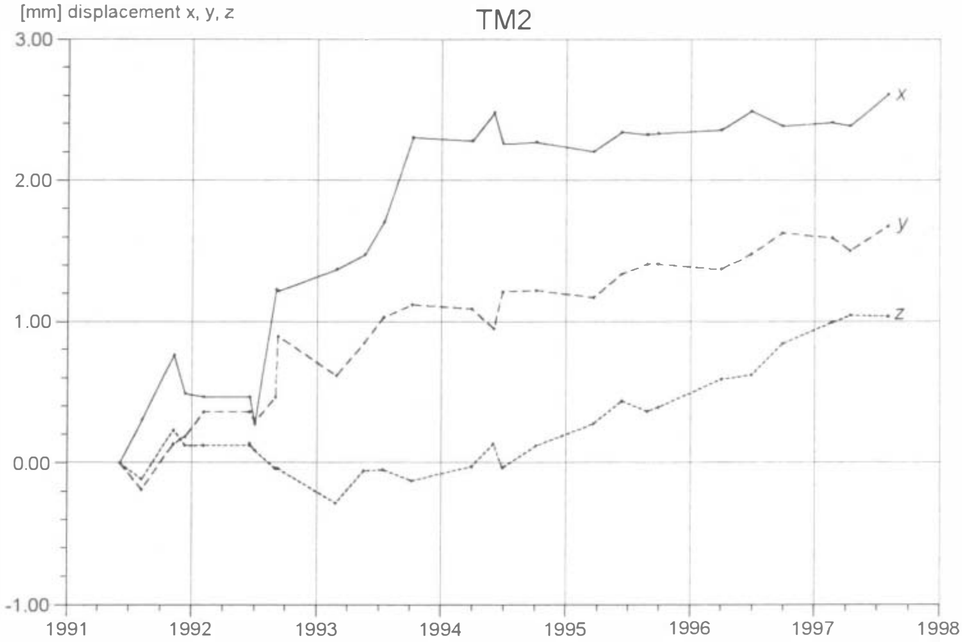


FIG. 6. Displacements recorded at the point TM2 on the outer side of the Perun Rock. Coordinates of the movements see Fig. 4.

Posuny zaznamenané v bodě TM2 na vnější straně Perunovy skály. Souřadný systém jako v obr. 4.

transparent, therefore shown as black rectangles. Below them, the model body was splitting to tower–like blocks which are moving slowly [illegible] of [illegible] free edge slope and after a time of internal preparation in the depth of the model body, where rheological processes were going on, it reached phases when the whole body was visibly involved in the defor [illegible] str [illegible] The last phases were characterized by an overall disintegration of deeper zones while some remnants of the tower heads rest sitting as boulders on the top of it. Marginal boulders show downslope inclination while two last boulders accepted an opposite position.

If we compare some of the advanced phases of the process as observed on the model with the block situation given in the photo of Fig. 3, we can see a good similitude. However, the detail given by the authors of the cross section of Fig. 2 does not coincide with our results and photo Fig. 3, as to the toppling orientation. There is block toppling outwards rather than back rotation at the eastern slope of Dreveník Hill. Obviously, the hill is in a stage of an advanced decomposition, which is most active in the marginal zones due to gravitational deformations. The flysh

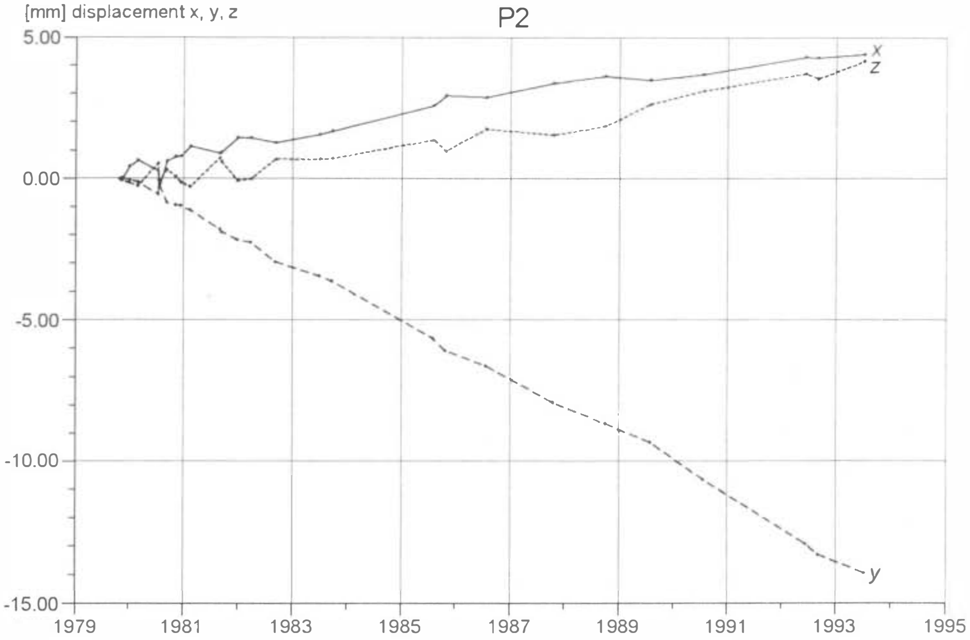


Fig. 7. Movements recorded at the point P2 in the old stonemasonry crack of the external fortification wall in the western section of the castle. Coordinates of the movements see Fig. 4.

Posuny zaznamenané v bodě P 2 ve staré trhlině zdi vnějšího opevnění v západní části hradu. Souřadný systém jako v obr. 4.

strata provide an unstable bedrock and their inclination plays an interesting role, which may explain the discussed difference. The side where it is dipping inward does not leave enough freedom for the tower roots to slip towards the external slope. Therefore, the towers start off in outward toppling instead. However, on the opposite side where the flysh strata are inclined a little downslope, the freedom exists, and the margin provides thus conditions for the towers to slip more easily at their base while toppling inwards.

Observer might notice a lot of other details in individual stages of the model, compare them with reality, and have a chance to make other interesting deductions. Now, when evidence of the present movements of Spiš Castle blocks has been gained by monitoring, we can see also well the coincidence of many facts and follow the experiment in more detail. Notably, it is even the Perun Rock at Spiš Castle, where the process of toppling will be of the same character as that of Dreveník. It was anticipated that it is due to the subsidence in local caves that rock blocks topple. However, the fan–like toppling is more generally due to inclination of the underlying beds. The presence of the caves can be considered generally as a result of the deformation process, a phenomenon of a certain deformation phase, rather

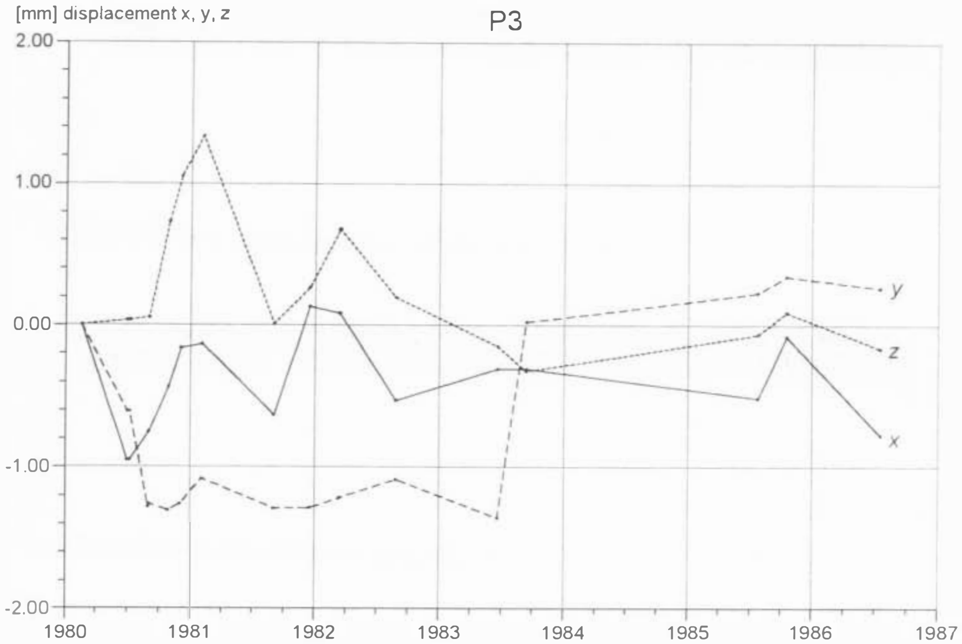


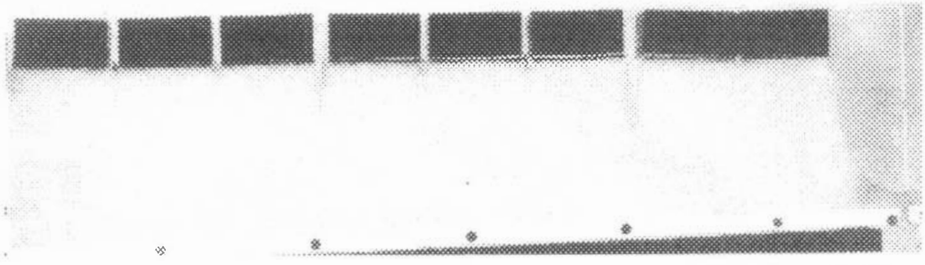
FIG. 8. Displacements recorded at the point P3 installed in the northern sector of the castle between high travertine blocks outside the fortification. Coordinates of the movements see Fig. 4.

Posuny zaznamenané v bodě P3. Tento měřicí bod je v severním sektoru hradu mezi vysokými travertinovými bloky vně opevnění. Souřadný systém jako v obr. 4.

than a special and necessary local condition responsible for such block movements.

5. CONCLUSIONS

Complex investigations on the Spiš Castle and Dreveník hills of Spiš Basin in Eastern Slovakia, which included model investigations and field monitoring, resulted in a proof that the travertine knobs are presently under an active process of block type slope deformation and may be given as a typical model example of such deformations. The process is due to conditions provided by flysh appearing in the underlying beds. The beds are slightly inclined which results in the uneven types of marginal block toppling, notably in the peculiar fan–like forms found at the eastern marginal zone of Dreveník Hill not common on the western side. Displacements in cracks reach rates of about 1 mm per year in the most deformable marginal sections of the hills. Other sections do not show any significant movements at present, being probably in a phase following catastrophic failure, which released energy and reduced the rate of the process. This can be derived from the models which show alteration of catastrophic falls with prolonged periods of slowdown. Such a situ-



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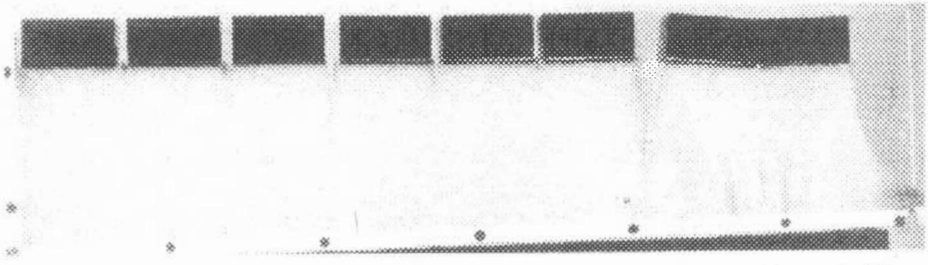

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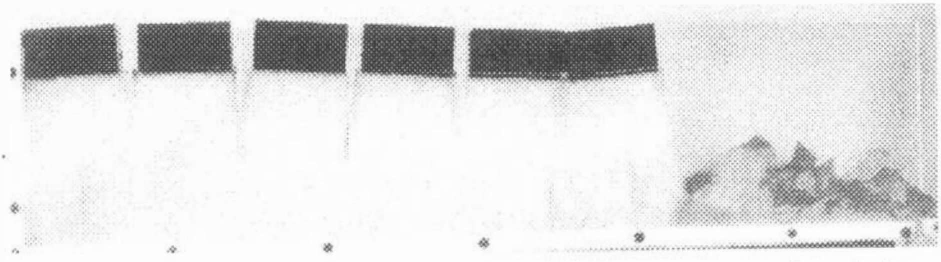

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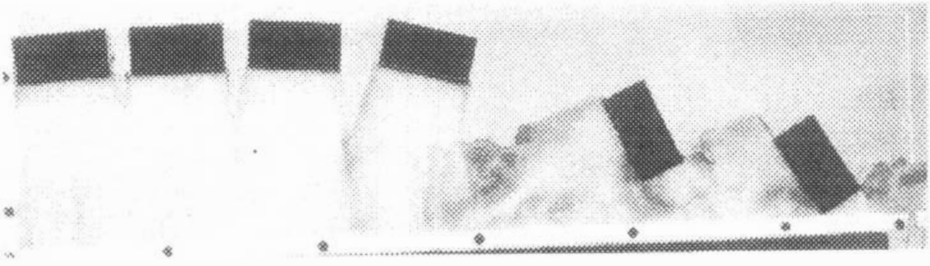

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FIG. 9a. Laboratory model of Dreveník marginal zone in time dynamics.

Important phases are given in series of photographs (Figs 9a and 9b) with time indication (hour:minute). (Notice the small inclination of the underlying strata, coincident with that natural found in flysh.)

a) Initial stages till the first phase of outside toppling;

b) Progressive stages of toppling till a final disintegration.

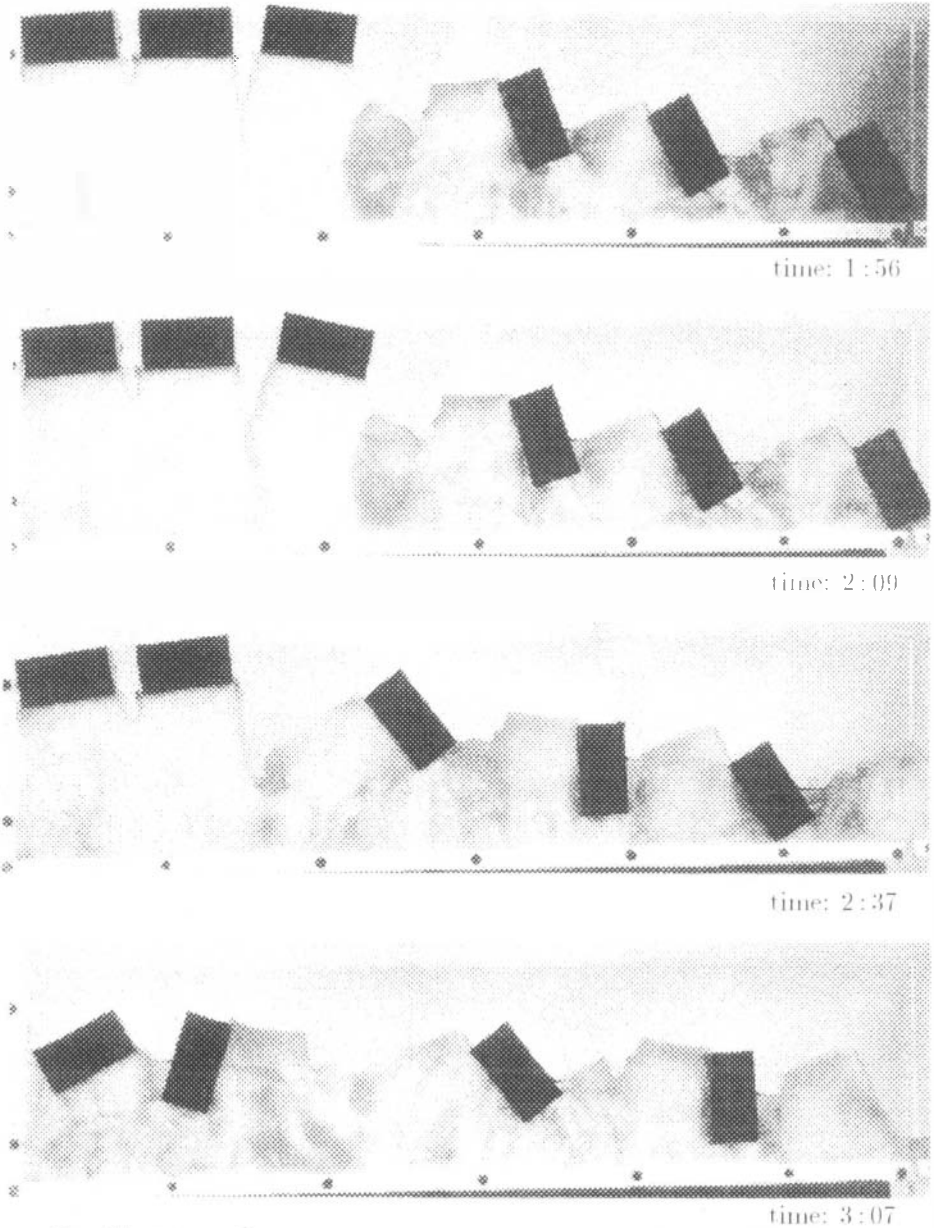

FIG. 9b. Laboratorní model okrajové zóny Dreveníku v časově postupující posloupnosti dynamického vývoje.

Důležité fáze vývoje jsou zachyceny na snímcích (obr. 9a a 9b) se záznamem času (hodina : minuta). Důležitým faktorem je malý náklon podloží, který souhlasí se skutečným náklonem v přírodě, ve flyšovém souvrství podloží bloků.

a) Úvodní fáze vývoje do stadia vyklánění bloků.

b) Progresivní fáze vyklánění bloků až k úplnému rozpadu struktury.

ation of present stability, holds probably for the section of the highest blocks of the northern edge of Spiš Castle, where any regular displacements could not be detected by monitoring at present. Models that were presented can be very useful in such investigations to show the dynamics which appear in the past, present, and future phases.

The example provides a lecture that instability must be expected under similar situations, where rigid blocks overrun plastic bedrock. This may be practically important in the case of many historical structures, like castles built on outstanding rock blocks. When they got to a stage of reconstruction, the long term stability question is to be considered. Any reconstruction calls for the need for seriously high funding, and cracking which would not be anticipated may result in loss of money. This is the case of Spiš Castle. Such a structure cannot be permanently stable, when having moving foundations. In such cases the design must take the problems of permanent slow deformations seriously into account.

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MODELOVÁ A POLNÍ STUDIE DYNAMIKY VZNIKU BLOKOVÝCH STRUKTUR NA SVAZÍCH

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Travertinové kupy ve Spišské kotlině východního Slovenska jsou vynikajícím příkladem plouživých blokových svahových pohybu. Jde zejména o Spišský hrad a vrch Dreveník. Výzkum (Nemčok & Svatoš, 1974) si povšiml starých trhlin v opevnění, které musely vzniknout později, než byl tento hrad ze 13. století dostaven a to v dusledku posunů základových bloku. Na snímku (obr. 1) je trhlina v opevnění u Perunovy skály s opevňovací věží na vrcholu. Tehdy také vznikl příčný řez sousedním Dreveníkem (obr. 2). Podle tohoto řezu bloky klouzají na tvárlivém flyšovém podloží do boků přiklánějíce se vrcholy k masívu jako karty. Tento zobecněný popis má však důležité výjimky. Např. snímek z východního svahu Dreveníku (obr. 3) vykazuje vějířovitou strukturu naklánějících se bloku. Také obr. 1 naznačuje náklony po svahu. Tyto odchylky jsou dusledkem odlišné dynamiky vývoje deformací a ovlivňují stabilitní poměry na svahu.

Za účelem ověřit skutečné pohyby těchto bloku v současnosti bylo v roce 1980 zahájeno dlouhodobé sledování mikroposunu s použitím terčových měřidel (Košťák, 1991) v několika významných trhlinách na Spišském hradě. Situaci měrných bodu na hradě a prvé výsledky popsal podrobně Fussgänger (1985). Později zde bylo sledování rozšířeno o další body (Vlčko et al., 1998), avšak opětovně tu byly vandalsky demolovány, takže hlavní údaje jsou z bodu uvnitř opevnění. Zde se proto podávají výsledky (obr. 4 až 8) založené především na puvodních bodech a shrnující fázi měření až do nedávného dokončení rekonstrukce hradu.

Přímé sledování potvrdilo, že blokové pohyby jsou na Spišském hradě aktivní v některých svahových sektorech, jako je sektor Perunovy skály. Soustavné dlouhodobé pohyby v trhlinách tu dosahují řádově 1 mm/rok. Naopak oblast vysokých věží severního výběžku pohyby nepotvrdila.

Byl rovněž zhotoven fotoplastický fyzikální model schematizované blokové struktury na tvárném podloží, který umožnil sledování časového dynamického vývoje její deformace v příčném řezu. Tento model byl zkonstruován originálním postupem (Košťák, 1977; 1982) umožňujícím výzkum vývoje porušení struktur v polarizovaném světle. Hlavní fáze deformačního vývoje v tomto modelu jsou zachyceny v sérii snímků na obr. 9. Je zde předveden vznik vějířovité struktury naklánějících se věží. Struktura vzniká v závislosti na náklonu podložních vrstev. Náklon směrem do nitra masívu brání částečně prokluzům v základech věží, zatímco na opačné straně náklon ven z masívu pohyby v základech po svahu podporuje. V obou případech však tvárnost podloží vede k dlouhodobým deformacím, svahovým pohybům a vzniku specifických

Tento výzkum upozorňuje na skutečnost, že tyto pohyby musejí být respektovány, vzdor tomu, že jsou malé. Zejména nákladné rekonstrukce historických objektů s nimi musejí počítat. Dlouhodobé pohyby v nestabilních sektorech podloží se nutně musí na rekonstruovaných objektech dříve nebo později projevit.