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Geodynamic hazard and risk assessments for sites close or in tectonic zones with shear movements

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Abstract No region is excluded from actions of recent geodynamic short- or long-term effects which can be observed even on the Earth's surface. The article delivers a geodynamic hazard assessment for the anthropogenic objects threatened by permanent shear movements occurring along tectonic faults and a way how to mitigate and/or eliminate the object risk. The proposed approach is applied to a case example of a motorway tunnel leading through rock masses where dynamically active zones with shear movements along their faults are expected. To detect the shear movements among rock masses, the contemporary satellite geodetic GPS methodology was used.

Keywords Geodynamic hazard and risk · Tectonic shear movements · Urban and territorial planning

Introduction

Lately a term of the deformation hazard appeared and was applied ordinarily in the cases where sedimentary covers and/or soil grounds were brought into unstable deformation states (FEMA 2004, 2005) like landslides, liquefactions, frost heaves, etc., arising mostly as post-earthquake or post-flood phenomena. Such deformations represented for example surface impacts of strong Denali 2002 earthquake to the Trans-Alaska pipeline (Carver et al. 2004; Cluff et al. 2003). Simply said, such kind of hazard should be classified as a post-earthquake hazard.

Contrary to the post-event deformation hazards, a few recent papers (Ovcharenko et al. 2002; Prashar et al. 2005; Trinh 2003) highlighted another type of a hazard, origin of which is linked with permanent long-term geodynamic processes. Shear movements along rock fractions in fault zone are one of these long-term actions. This type of hazard is classified in the paper as geodynamic one. The hazard and risk assessments for objects like tunnels, road galleries, buried lifelines, bridges, elongated buildings, etc., located in or crossing the geodynamic active fault zones are the subject of this paper.

Geodynamic hazard and risk assessment

Recent geodetic techniques are able to detect long-term motions on the Earth surface if relatively long observation periods are applied. Contrary to short-term natural destructive actions caused by earthquakes, wind-gusts, etc., long-term geodynamic destructive impacts to anthropogenic objects can be significantly reduced or excluded. Even if slow geodynamic processes in tectonic fault zones exist, anthropogenic objects close to and/or inside the zones can be affected intensively (Fig. 1a).

Contrary to natural hazards caused by irregular short-term events (earthquakes, tsunamis, winds, volcanoes, etc.), the geodynamic hazard linked with permanent shear movement along the fault cannot be

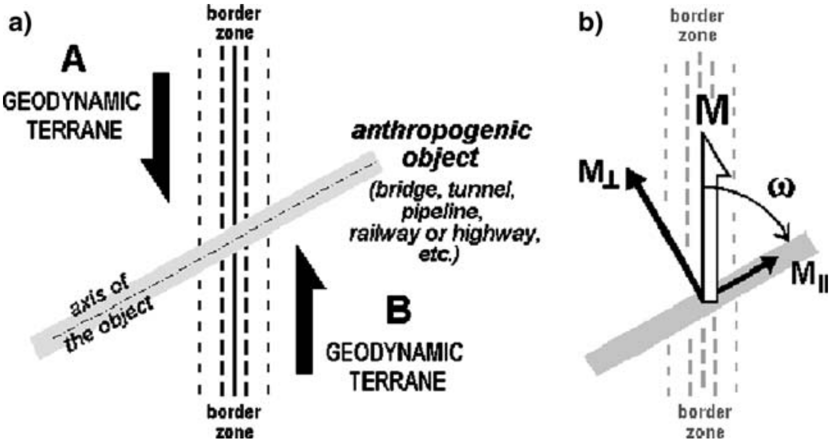

Fig. 1 Anthropogenic object situated within **a** a border zone of geodynamic terranes A and B and **b** their long-term shear movements along their border zone

expressed in a form of conditional probabilities of event occurrences because of regular and continuous long-term actions of geodynamic processes. Thus, for the investigated object, the maximum value of such geodynamic hazard $H_{\max}$ corresponds to the shear movement velocity M (mm/year) acting in the object area basement (Fig. 1b)

$$H_{\max}=M=\left(M_{\|}^{2}+M_{\perp}^{2}\right)^{1/2}. \tag{1}$$

An important role in the hazard assessment of the object plays its orientation to the shear movement direction: the angle ω (°) between the main axis of the object and the movement direction divides the M shear movement into two components acting along $M_{||}$ (mm/year) and across $M_\perp$ (mm/year) the object axis, respectively. As evident, only the perpendicular shear movement $M_\perp$ affects the object (Fig. 1b).

This fact places in the hazard and risk assessments the angle ω into two principally different positions: for already existing objects the angle ω has to be taken into account as the hazard parameter, but for objects under design as the risk parameter. Thus, the real geodynamic hazard H determined for the object and the related risk R must be assessed from the following two viewpoints:

(a) for the existing objects

$$H=M*\sin\omega=M_\perp \tag{2a}$$

and

$$R=c*H*V*t*R_0 \tag{3a}$$

but

(b) for the objects under the design

$$H_{\max}=M \tag{2b}$$

and

$$R=c*H_{\max}*\sin\omega*V*t*R_0. \tag{3b}$$

In the second case, it is necessary to take into the hazard assessment as its maximum site value $H_{\max}$ because only the angel ω applied in the design will determine the real value H for the object. In relations 3a and 3b, c is a constant evaluating an object interaction with geological media, V is a vulnerability function, ω is an angle mentioned above, t is an expected lifetime (year) of the object and R_0 is a specific value of the object risk depending on the structure design.

The vulnerability function V of the object and its elements have to involve all structural responses to long-term compressions, tensions and/or torsions. Cohesive thresholds of structural elements depend on technical parameters of the object. Similar to vulnerability functions applied for short-term natural impacts (earthquakes, winds, etc.), the functions V for the geodynamic risk determination have to involve responses of structure and its structure elements reactions. The relations given above show that the angle ω can significantly mitigate or eliminate both the hazard H and the risk R values: the smaller ω, the smaller H and R assessments (Fig. 1b). The interaction materials put between the object and surrounding geological media should be able to mitigate substantially geodynamic long-term negative impacts to the object. For example, if filling of an ambient space round a tunnel tube is plugged by ductile substances, then deformations occurring in surrounding rock masses can be absorbed. Likewise, if motorway embankments contain tractable materials, then they are able to keep both long-term deformations being under way in their basement rocks and short-term ones caused by seismic strong ground vibrations, etc.

Although physical aspects of individual components in the relations 3a and 3b are clear, nevertheless their particular values applied to geodynamic risk mitigation need still additional attention.

Case example: the NE part of the Bohemian Massif (Central Europe)

In 1997, the Czech-Polish regional geodynamic East Sudeten network was established in the NE part of the Bohemian Massif (Schenk et al. 2002, 2003). The eight annual GPS 2-day epoch measurements with a sampling rate of 30 s were realized in 1997–2004 on 14 network sites (Fig. 2) mostly by the Ashtech receivers and antennas. Standard deviations of the annual site movement velocities assessed from all eight epoch data have not exceeded ±0.5 mm/year in the horizontal and ±1.5 mm/year in the vertical components.

Figure 3a, b presents horizontal and vertical annual velocities detected on the East Sudeten network sites. A clustering of the arial median velocities allowed probable geodynamic terrannes to be identified (Fig. 3c). The movements at the Lower Jeseník Mts. and the Drahan Higland terrane (LJ~D) and the Lower Silesian-Opole terrane (LS~O) displayed the NNE trends while the SSW movement trends were detected for the High Jeseník Mts. terrane (HJ). Even if the terrane delineation could be discussed, the existence of shear movements in the Moravo–Silesian thrusting zone (6 in Fig. 2) is evident. Since a motorway tunnel planned under the Červená hora Saddle area is located just in the thrusting zone, for this locality the problem of geodynamic hazard caused by existence of the shear movements along faults appeared.

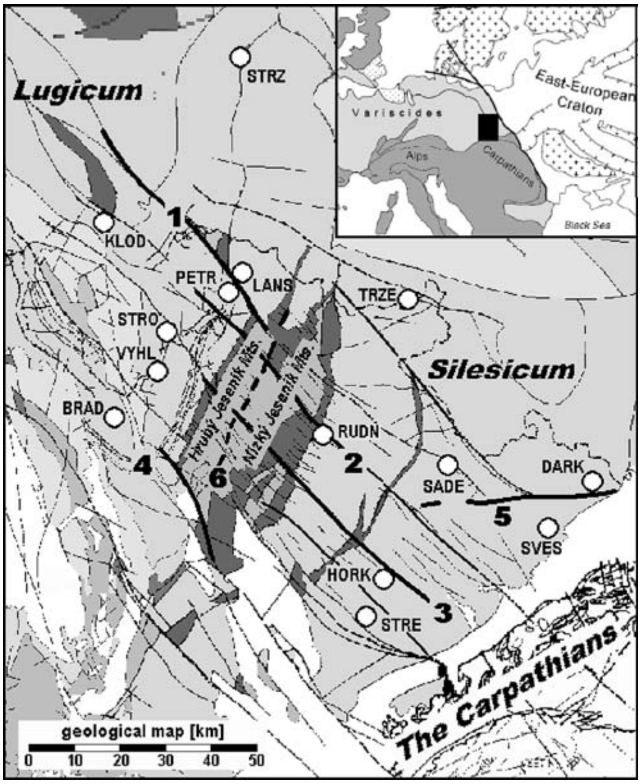

Fig. 2 The East Sudeten network sites in the NE part of the Bohemian Massif (Central Europe) and main tectonic faults: *1* Marginal Sudetic fault, *2* Bělá fault, *3* Klepáčov fault, *4* Bušín fault, *5* Opatovice fault zone and *6* Červená hora fault zone

Besides the strike-shear movements discussed above, shear movements in a normal sense were detected too: the LJ~D terrane displays subsiding tendencies while the HJ terrane exhibits uplifting trends (Fig. 3b). The movement disconnections have been initiated in the last Miocene and recent geological and geodetic investigations confirmed them (Buday et al. 1995; Kontny 2004; Skácel 2004; Vyskočil 2002).

Geodynamic hazard and risk for the tunnel designed at the Červená hora Saddle

Recent principles applied in a territorial and/or urban planning require to keep the environment and inevitable to minimize its disruptions. The hazard assessment for the planned motorway tunnel crossing a protected Jeseníky hilly landscape area at the Červená hora Saddle (Figs. 2, 3) is presented. The Saddle finds itself in the central part of the East Sudeten network.

The recent motorway route (bold line in Fig. 4) rises by many bends from south over 400 m drop in a steep hillside up to the Červená hora Saddle and then again downwards. In the area rock complexes display faulting related to the observed movements (Fig. 3a, b). The most threatened motorway part would be a tunnel segment that has to pass the area of expected shear movements in the border fault zone (6 in Fig. 2) between the HJ and LJ~D terranes (Fig. 3c).

To evaluate the hazard for the motorway tunnel at the Červená hora Saddle, a regional pattern of shear movements and their azimuth orientations had been taken into account. The detected movements were qualitatively and quantitatively estimated. The expected maximum velocities of the sinistral shear movements M along fault planes were assessed. They did not exceed values of 0.5 mm/year. If the designed tunnel axis with local faults forms an angle $\omega \leq 20$–$25°$, then the velocity movement components (Fig. 1b) could achieve $M_{\parallel} \approx 0.45$ mm/year and $M_{\perp} \approx 0.15$ mm/year.

In the section Geodynamic hazard and risk assessment, the relation 3b allows the geodynamic risk R for newly designed objects to be determined. In our case, the risk evaluation for the tunnel tube at the Červená hora Saddle will depend on the interaction constant c, vulnerability function V of the tube, its structure elements R_0, angle ω and expected lifetime of the object t.

Introducing lower angle ω to the tunnel design will cause a lessening of the tunnel vulnerability and possible geodynamic affects caused by the original maximum

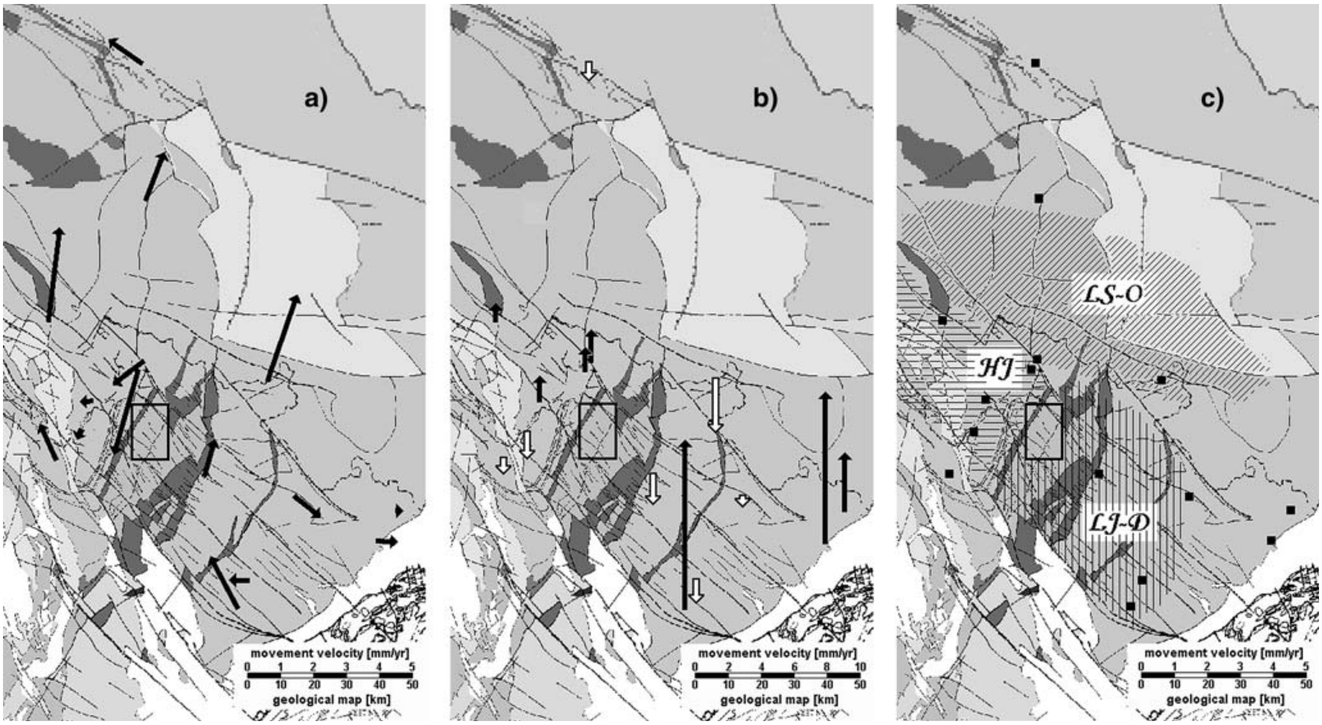

Fig. 3 Horizontal (**a**) and vertical (**b**) annual site velocities (mm/year), **c** geodynamic terranes: *HJ* the High Jeseník Mts., *LJ*~*D* the Lower Jeseník Mts.—the Drahan Higland and *LS*~*O* the Lower Silesian-Opole area; *frame area* region of the Červená hora Saddle, and *black squares* GPS network sites

shear movement M will be mitigated only to the value of $M_{\perp} \approx 0.3\ M$. Then the maximum geodynamic hazard value $H_{\max}$ of the site will be lowered to one-third and by this way the tunnel tube lifetime will increase more than three times without substantial restorations. Moreover, if ductile materials are chosen in accordance with the interaction constant c and plugged between the tunnel tube and geological media, the absorption of total geodynamic deformations round 0.1 m and the tunnel tube lifetime t of 70 years could be expected.

Likewise, it is recommended for motorway bridges the angle $\omega \leq 30°$ and for motorway segments with roadbed causeways of variable thicknesses the angle $\omega \leq 45°$.

Conclusion and recommendation

Aspects of the long-term geodynamic actions, namely, the permanent shear movements along faults, to anthropogenic objects and a way how to estimate their possible damage threats were delivered. The common approach of the hazard and risk assessments was modified and strategies of the risk control, its mitigation and/or elimination, were exhibited on a case example of the

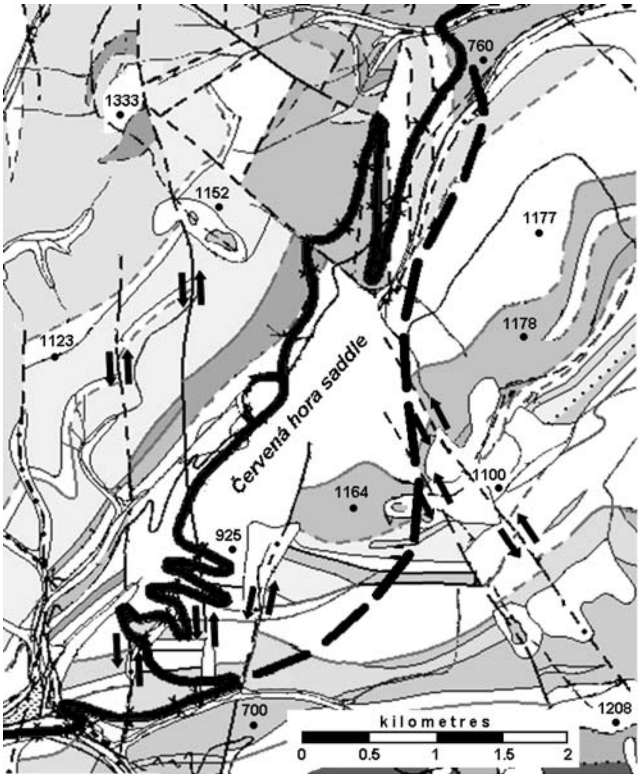

Fig. 4 Recent mountain motorway (*heavy line*) over the Červená hora Saddle area going to a height of 1100 m above sea and proposed motorway tunnel (*heavy dashed line*) in a height of 700 m

tunnel tube designed in the region where the shear movements are expected. Proposed methodology can be applied without or with minor changes to other motorway elements, railway tracks, bridges, pipeline techniques and elongated objects, resistances of which should be protected against permanent long-term geodynamic impacts. The rather important feature of this approach is a fact that the hazard values can be controlled by the object orientation with respect to the direction of total movement action. Specific elements in the object and ductile materials put between the object and surrounding rocks can increase substantially dynamic protection of the object and its expected lifetime.

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