ACTIVE FAULTS AT STRUCTURE'S FOUNDATIONS: DEFINITION AND ITS INFLUENCE ON HAZARD ASSESSMENT

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Abstract

Different scientific papers as well as the industrial, regional, national and international regulatory documents and guidelines define term "active fault" in different ways, which affects resultant hazard assessment significantly. Most of definitions focus on time span in which fault motions took place in the past, which differs from ~10 000 years (Holocene) to more than 2 million years (Quaternary period). However, engineering, technical approach to study any hazardous natural phenomena requires quantitative assessment of the expected impact. In case of an active fault, such impact depends either on the single-event displacement value or on the rate of permanent motions, which should be used, among others, as the input parameters for the design of any protection or mitigation measures. The threshold values of these parameters must be included in active fault definition along with the above time span. The definition considering both time interval of the activity manifestation and the ability of structures to sustain these movements was proposed and included in Russian seismic code, which defines active fault as follows: "Fault is considered as being active if there is evidence of permanent or periodical displacements in the Late Pleistocene – Holocene time (during last 100,000 years), with such single-event offset value or displacement rate that poses a threat to the structure and requires special engineering or placement measures to ensure its safety". Such approach implies close cooperation between earth scientists studying active faults on the one hand and engineers designing protection or mitigation measures and project managers assessing risks on the other hand. Such cooperation should start from the beginning, at the site/route selection stage of project implementation, when it is especially important to identify the potentially hazardous phenomena correctly or to be sure that they are absent and could not affect the structure. Active fault parameters necessary for the design such as its desirable location accuracy, details of motion kinematics and the threshold displacement values must be listed in the technical assignment for site investigations provided to the Contractor who will perform the design. It should help avoiding both under- and overestimation of fault-related hazards that could cause the significant economic losses. The proposed approach is focused on discrimination of faults that cross construction sites or lifeline routes and could affect the engineering structures directly. Seismic hazard assessment in which causative faults identification also plays a critical role, allows much broader definition of the tectonic structures that can be considered as active and, thus, have the potential to generate large earthquakes.

Keywords: active fault; displacement; hazard assessment; site investigations

1. Introduction

Active faulting at a construction site, especially associated with large earthquakes, is one of the most destructive natural phenomena that can be hardly withstood by most of types of structure and lifelines. That is why statement in the engineering survey report that the structure's foundation or lifeline route is crossed by active fault can be critical for any further activities. Both under- and overestimation of fault-related hazards can result in significant economic losses. Missing of active fault that crosses the site, or missing of evidence indicating fault activity increases risk significantly. On the contrary, erroneous identification of such a hazardous feature would either stop further project implementation or increase its complexity and cost without a reasonable basis. Thus, the correct definition of the tectonic structure that must be classified as an "active fault" in the construction codes is of high practical importance.

Numerous research papers on natural hazards define “active fault” in different ways. Variable definitions are included in the regional, national and international guidelines and codes regulating construction sites or lifeline routes selection and design of the efficient protection or mitigation measures. This paper describes active fault definition included in new Russian seismic construction code [1] and based on the experience gained in the course of seismotectonic investigations of dam construction sites and trunk pipeline routes.

2. Time interval

The discussion on the time interval that must be considered to classify a fault as an "active" or "inactive" lasts for decades starting from 70th of the XXth Century [2-10]. The critical review of these definitions was provided more than 20 year ago by A. Nikonov [11]. In most of definitions the time span in which the latest fault motions have taken place to consider this structure as an "active" ranges from 10,000 – 11,000 years (Holocene) to ~100,000 years, though some researchers extend this time interval up to 2.6 million years – the entire Quaternary period (e.g. [12]).

Regional, national and international construction codes and guidelines also define this time interval in different ways. For example, the International Atomic Energy Agency (IAEA) requiring most conservative approach for natural hazards evaluation recommends to consider period when past movement(s) had occur in a rather broad manner, with due regard to the "activity" of the area, i.e. the longevity of the earthquake recurrence intervals [13]. It should be mentioned that the term "capable fault" is used in this document, instead of "active fault". However, its definition: "Capable fault – a fault that has a significant potential for displacement at or near the ground surface" allows considering it as a synonym of an "active fault". In the regions with short earthquakes' recurrence intervals those faults that experienced displacements during last tens of thousands of years (i.e. the Upper Pleistocene–Holocene) should be considered as capable, while in less active regions such conclusion can be done if evidence of movements during the entire Quaternary Period has been found. The disadvantage of such definition is that in some parts of the world with poor state of knowledge of the earthquake history we do not have enough data (both historical and paleoseismological) to make well grounded decision how long the real recurrence interval is, which increases the subjectivity of active faults discrimination.

Another international agency – the International Commission on Large Dams (ICOLD) defines active faults in a rather controversial way [14]: "Active fault: a fault, reasonably identified and located, known to have produced historical earthquakes or showing evidence of movements in Holocene time (i.e. in the last 11,000 years), large faults which have moved in Latest Pleistocene time (i.e. between 11,000 and 35,000 years ago) and major faults which have moved repeatedly in Quaternary time (1.8 million years)". The ambiguity of the terms "large fault" and "major fault" does not allow following these recommendations strictly. Moreover, evidence of recent movements along significant faults (word collocation "significant fault" is used as a free use analogue of both "large" and "major" faults) are often identified not continuously along the entire fault length, but discretely at some short fault segments, so that the decision to consider them either as a "reasonably identified and located fault" or as a "large/major fault" could be quite subjective too.

The American Lifelines Alliance [15] recommends to consider faults to be active "if they have moved one or more times in the last 10,000 to 11,000 years, but they may also be considered potentially active when assessing the hazard for some applications even if movement has occurred in the last 500,000 years", which also provides rather high level of ambiguity when making decision on the state of a particular fault.

One of the most strict and clear definitions is provided by the California Department of Water Resources, Division of Safety of Dams [16]. This agency defines an active fault as "having ruptured within the last 35,000 years. A conditionally active fault is defined as having ruptured in the Quaternary, but its displacement history during the last 35,000 years is unknown". An important point is that the criterion of fault inactivity is defined in these Guidelines as well. Fault is considered as inactive if "a confidently located fault trace is consistently overlain by unbroken geologic materials older than 35,000 years". Similar approach is described in [12], where fault is considered as active "unless it is sealed by deposits or landforms not younger than the LGM (Last Glacial Maximum)".

In Russian construction codes prior to [1] term "active fault" was not defined except the [17] regulating nuclear power plants placement, where active fault is defined as a fault along which relative displacement of crustal blocks of 0.5 m or more have occurred during Quaternary period or modern tectonic movements with a rate of 5 mm/year or more take place. Further discussion on this definition that includes time interval as well as the displacement value / rate will be presented in the next section.

Considering that some well studied faults demonstrate recurrence intervals between surface rupturing events exceeding 10,000 years significantly [18, 19, 20], as well as the workability and accuracy of the most commonly used Quaternary dating methods [21], time interval up to ~100,000 years is recommended to be analyzed during site investigations to discriminate active and inactive faults. Such approach seems to be not excessively conservative and allows assessing the probability (or, at least, the possibility) of the future surface faulting in case of long recurrence intervals between identified rupturing events (Fig. 1). If, however, the recurrence interval exceeds ca. 100 000 years, chance that next event will occur during structure normative lifetime (that rarely exceeds 100 years) is so low that such event, even if it could not be totally excluded, can be considered as a force majeure.

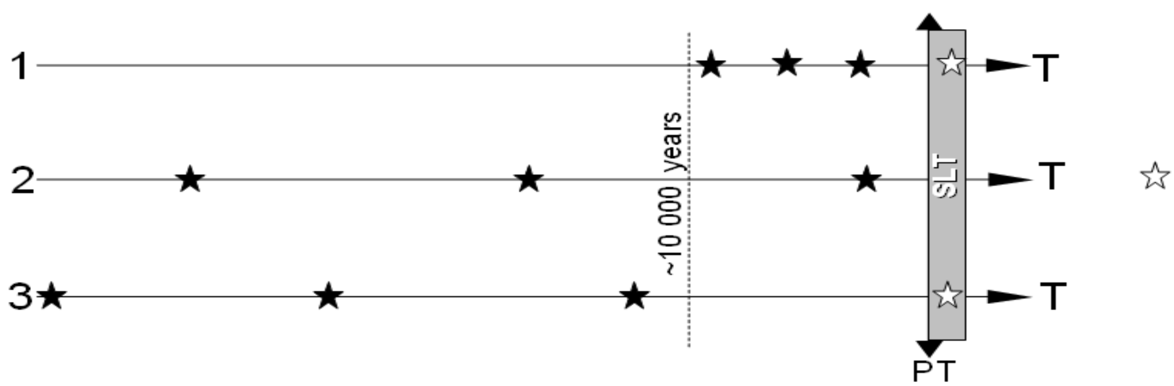

Fig. 1 – Idealized successions of surface rupturing events (earthquakes). T – time scale; PT – present time; SLT – structure lifetime; black stars – past surface rupturing events identified and dated; white stars – assumed future rupturing events. 1 – short (<<10,000 years) recurrence intervals and high probability of next event within the structure lifetime; 2 – long (>>10,000 years) recurrence intervals and low probability of next event within the structure lifetime (anticipated in far future) despite young age of the latest event; 3 – long recurrence intervals (same as in 2) and high probability of next event within the structure lifetime despite age of the latest event exceeding 10,000 years

It should be pointed out that the history of fault movements is always studied from the present to the past. Thus, if evidence of two or more rupturing events during this period of time is identified, it is enough not only to consider fault in question as an active one, but to estimate the recurrence interval for practical purpose. It can be exemplified by the study of the surface rupture in the Chong Aksu River valley in Kyrgyzstan, north of the

Issyk-Kul Lake that was activated last time by the 1911 M8.2 Kemin earthquake [22]. We found evidence of two rupturing events marked by the successive colluvial wedges both of which are younger then the buried soil layer dated 1490 - 1660 AD overlaid by these wedges. They indicate short – few centuries-long only – recurrence interval between two latest events. However, previous rupturing event(s) along the same fault had occurred at least ca. 6000 years ago. Moreover, one of the even older events formed the upslope-facing scarp and sediments dated 18,200-17,538 BC accumulated behind this tectonic dam (similar to the phenomena cased by 1911 earthquake). These data indicate temporal clustering of strong rupturing events with recurrence intervals of the order of few hundreds years divided by “stable” periods lasting for many thousands years. However, since it remains unknown if the last temporal cluster finished with the 1911 Kemin earthquake or not, short recurrence interval should be considered for hazard assessment of any construction site located at or close to this fault zone.

On the other hand, if no recent rupturing event would be identified, the recommended long (100,000 years) period of time during which fault in question should demonstrate evidence of movements to be considered as an active one, allows reasonable statement on its activity/inactivity, if rupture history would correspond to the situations 2 or 3 shown on Fig. 1.

3. The threshold displacement value

Most of the above definitions include words or word collocations such as "significant potential for displacement" [13], "showing evidence of movements", "have moved in ... time/years" [14, 15], or "having ruptured within ... years" [16]. But the question arises, if these words can characterize amount of movement quantitatively? No doubts that the single-event offset of, say, one meter or more is "significant" and must be considered for the design of any type of structure. But it is known that more then 20 earthquakes with magnitudes up to 6.8 produced surface ruptures with maximal offsets from less than 1 cm to 10 cm only [23, 24]. Such small displacements, first, could be hardly identified centuries and millennia after the event, and, second, can be sustained by such structures as, for example, trunk pipelines [V.M. Ziuzina, personal communication] or earth fill dams [25] even without special protection measures. Moreover, since fault movements could take place not only in connection with earthquakes, but also in the form of the tectonic creep, minimal threshold values of permanent fault movements should be defined to avoid consideration of a particular fault as an active one if this rate is too low.

As mentioned above, the definition proposed in RB-019-01 issued by Russian Federal Service for Nuclear Supervision [17] includes the threshold value of relative displacement of 0.5 m during Quaternary period or the 5 mm/year rate of the modern tectonic movements. The latter value seems to be exceptionally high because if permanent displacements with a rate of 4 mm/year (less than the threshold value) would take place, the cumulative offset during the NPP lifetime of about 30 years would be 12 cm, which it absolutely unacceptable.

The threshold relative displacement of 0.5 m during Quaternary period for the recurrent movements, recommended in [17] seems to be practically unworkable too. First, it is very difficult to identify such a small offset if it occurred prior to Late Pleistocene – Holocene epoch. If some old planation surface was displaced long ago, most likely that the 0.5-1.0 m high fault scarp or similar lateral offset would be unidentifiable due to long-term erosion. Besides, if rupture had been buried by sediments and, thus, can be identified in the cross-section only, but not expressed in the modern relief, such a small offset could be found just by chance. Moreover, since it is a threshold value, such offset should be maximal for the fault in question. It is known, however, that slip distribution along earthquake surface ruptures are quite nonuniform and maximal offsets are typical of a very small section of rupture – less than 5% of its total length on average [23, 26, 27]. It decreases the chance to find such a small portion of a very old surface rupture during site investigations.

On the other hand, one can imagine the hypothetical situation that the construction site or lifeline route is crossed by the newly formed Holocene surface rupture with 40 cm maximal displacement that have not been preceded by any older Quaternary event. According to [23] such displacement corresponds to M_w=6.4 earthquake; according to [24] it could be associated with earthquake with M_s not less than ~5.2. Both estimates are significant, so such events must be considered as hazardous and corresponding fault as a causative or active.

However, formally, it should not be considered as an active one since the cumulative Quaternary offset does not reach the 0.5 m threshold value.

Our approach is based on the statement that the study of any hazardous natural phenomena for the design purpose requires quantitative assessment of the expected loads. Otherwise engineers can neither propose and design effective protection or mitigation measures, nor make sound decision on the necessity to shift to another site or to change a lifeline route. In case of active faulting, such loads are predetermined either by single-event displacement value or by the permanent motion rate. An important point is that different types of structures and lifelines are differently sensitive to fault displacements. For example, 5-10 cm thermal and hydrodynamic deformations are common for flexible trunk pipelines, both above-ground and buried, and possibility of such motions is considered by the "standard" design [V.M. Ziuzina, personal communication]. Offsets up to ca. 1 m could be acceptable for earth-fill dams [25, 28]. On the other hand even 1-2 cm displacements could be unacceptable for high-speed railways, for example. The concrete dams and other brittle structures are also much more sensitive for relative motions of the adjoining blocks in their foundations [25, 28]. Based on these considerations the following definition was proposed and accepted for Russian seismic code [1]: "Fault is considered as being active if there is evidence of permanent or periodical displacements in Late Pleistocene-Holocene time (during last 100,000 years), with such single-event offset value or displacement rate that poses a threat to the structure and requires special engineering or placement measures to ensure its safety".

4. Discussion and Conclusions

The proposed definition considering the ability of structure to sustain surface faulting allows classifying tectonic structures that cross the construction site or lifeline route for the engineering purpose more informatively then purely "time-specifying" definition. It allows providing just that information about faults that will be used by engineers and project managers in their work.

Its practical utilization, however, implies close cooperation between earth scientists studying active faults and engineers designing protection or mitigation measures and project managers assessing corresponding risks. Such cooperation should start from the initial stage of project implementation, during the site/route selection, when it is especially important to identify the potentially hazardous phenomena correctly or to be sure that they are absent and could not affect the structure. Active fault parameters necessary for the design such as its desirable location accuracy, details of motion kinematics and the threshold displacement values must be listed in the technical assignment for site investigations provided to the Contractor who will perform the design.

It should be pointed out that the proposed approach is focused on discrimination of faults that cross construction sites or lifeline routes and could affect the engineering structures directly. Seismic hazard assessment in which causative faults identification also plays a critical role, allows much broader definition of the tectonic structures that can be considered as active and, thus, have the potential to generate earthquakes.

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6. References

[1] SP 14.13330.2014. *Seismic Construction Code*. SNiP II-7-81* (2014): Ministry of construction and housing and communal services of Russian Federation, Moscow (in Russian).

[2] Allen CR (1975): Geological criteria for evaluating seismicity. Geological Society of America Bulletin, **86**, 1041–1057.

[3] Nikonov AA (1977): *The Holocene and modern movements of Earth crust*. Moscow, Nauka Publishers, (in Russian).

[4] Research Group for Active Faults (1980): *Active Faults in Japan—Sheet Maps and Inventories*. University of Tokyo Press, Tokyo (in Japanese with English abstract).

[5] Wallace RE (1981): Active faults, paleoseismology, and earthquake hazards in the western United States. *Earthquake Prediction: An International Review* (D. W. Simpson, and P. G. Richards, Eds.), Maurice Ewing Ser. 4, pp. 209–216. American Geophysical Union, Washington, DC.

[6] Ding G (1982): Active faults in China. *Proceedings of the 1979 Yinchuan Conference. Seis. Comm. China* Seismologica. Society, Seismology Press, Beijing, China (in Chinese).

[7] Slemmons DB, dePolo CM (1986): Evaluation of active faulting and related hazards. *Active Tectonics. Studies in Geophysics*, National Academic Press, Washington, DC, 45–62.

[8] Research Group for Active Faults (1991): *Active Faults in Japan—Sheet Maps and Inventories, Revised edition*. University of Tokyo Press, Tokyo (in Japanese with English abstract).

[9] Stewart I, Owen LA, Vita-Finzi C (Eds) (1993): *Neotectonics and Active Faulting.* Zeitschrift für Geomorphologie, Suppl. Bd. **94**.

[10] Trifonov VG, Machette MN (1993): The world map of major active faults project. *Ann. Geophys. (Annali di Geofisica)* **XXXVI** (3–4), 225–236.

[11] Nikonov AA (1995): Active faults definition and problem of identification. *Geoecology, Engineering Geology, Hydrogeology, Geocryology,* (4), 16-27 (in Russian).

[12] Galadini F, Falcucci E, Galli P, Giaccio B, Gori S, Messina P, Moro M, Saroli M, Scardia G, Sposato A (2012): Time intervals to assess active and capable faults for engineering practices in Italy. *Engineering Geology*, **139–140**, 50–65.

[13] Seismic Hazards in Site Evaluation for Nuclear Installations (2010): *IAEA Safety Standards Series* No. SSG-9. Vienna.

[14] Selecting seismic parameters for large dams guidelines (2010): *ICOLD Bulletin* **148**.

[15] The American lifelines alliance (2005): *Guideline for Assessing the Performance of Oil and Natural Gas Pipeline Systems in Natural Hazard and Human Threat Events. Part 2 Commentary*.

[16] Fraser WA (2001): *Fault activity guidelines*. California Department of Water Resources, Geology Branch, Division of Safety of Dams. http://www.water.ca.gov

[17] Federal Service for Nuclear Supervision (2001): *Seismic hazard evaluation of the nuclear- and radioactive-hazardous facilities placement sites based on the geodynamics data RB-019-01*, Moscow.

[18] Kumamoto T (1998): Long-term conditional seismic hazard of Quaternary active faults in Japan. *J. Seismol. Soc. Japan*, **50**, 53-71.

[19] Kozhurin A (2009). Personal communication.

[20] McCalpin JP (Ed.) (2009) Paleoseismology. *International Geophysics Series*, **95**. Elsevier, 2nd Edition.

[21] Walker M (2005) Quaternary dating methods. Willey.

[22] Abdrakhmatov KE, Delvaux D, Havenith H-B, Strom AL, Vittori E (2012): Temporal clustering of the North Tien Shan strong earthquakes: evidence from the Chong-Aksu trench. *33rd General Assembly of the European Seismological Commission Abstract*.

[23] Wells DL, Coppersmith KJ (1994): New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement", *Seismological Society of America Bulletin*, **84**, 974-1002.

[24] Strom AL, Nikonov AA (1997): Relationships between seismic fault parameters and earthquake magnitude. *Izvestiya, Physics of the Solid Earth,* **33**, (12), 1011-1022.

[25] Wieland M, Brenner RP, Bozovic A (2008): Potentially active faults in the foundations of large dams Part I: vulnerability of dams to seismic movements in dam foundation. *Proc. of the 14th World Conference on Earthquake Engineering, October 12-17, 2008, Beijing, China*. 14_S13-50.

[26] A.L., Strom and A.A. Nikonov (2000): The distribution of slip along seismogenic faults and incorporation of nonuniform slip in paleoseismological research", *Volcanology and seismology*. **21**, 705-722.

[27] Strom A, Ivaschenko A, Kozhurin A (2009): Assessment of the design displacement values at seismic fault crossings and of their excess probability. *Geological engineering problems in major construction projects. Proceedings of 7th Asian regional conference of IAEG, 9–11 Sept 2009, Chengdu, China*, 139-143.

[28] Neotectonics and dams. Guidelines and case histories. (1998): *ICOLD Bulletin* **112**.