

Seismotectonics and seismic hazard in the Roer Valley Graben: an overview

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Introduction

The potential for moderately destructive earthquakes in the Roer Valley Graben region has long been recognised and when the Roermond earthquake occurred in April, 1992, the local and international communities were once again roused to reassess their ideas on the level of earthquake hazard. To assist in this process at an early stage, the preliminary and ongoing scientific and engineering studies initiated in response to this earthquake were reported at a workshop at Veldhoven, the Netherlands, on January 20–22, 1993. In this overview the editors have summarised the state of knowledge and results of new investigations as presented at the workshop and in the papers assembled in this special issue of 'Geologie en Mijnbouw'.

Geology and tectonics

It is well known that the Roer Valley Graben is a branch of the Rhine Graben system which belongs to the extensive reactivated Cenozoic rift system in western Europe. In this region, earthquake focal mechanisms are the principal source of information on the current regional crustal stress field. Attempts to model the stress tensors within the European plate and to eliminate alternative hypotheses by circumstantial evidence suggest that the contemporary tectonic activity in the Rhine Graben system is driven by regional interplate interaction. Within the Rhine Graben system, only the Roer Valley Graben displays a significant component of active extension, suggesting a regional SW-NE direction of the minimum horizontal stress component. This configuration of stresses explains also the *in situ* stress observations and the dominantly strike-slip earthquake mechanisms in the N-S trending Upper Rhine Graben region. Relatively

large earthquakes, like the 1992 Roermond earthquake, represent significant stress release and, therefore, yield more probable regionally-determined stress fields. The overall inferred normal dip-slip mechanism of fault movement during the event confirms the existing tectonic model convincingly.

Regarding neotectonic movements, it is known that since the beginning of the Quaternary the rate of subsidence has increased markedly within the Roer Valley Graben, reaching maximum values of 0.8 mm/year along the north-eastern boundary fault. Slip on this fault, the Peel Boundary Fault, was responsible for the 1992 Roermond event. Geomorphological and scant seismological evidence suggests also a recent strike-slip motion component along the Peel Boundary Fault. This is interesting because the orientation of this fault with respect to the general direction of the contemporary maximum horizontal stress component suggests overall normal dip-slip reactivation.

Unfortunately, detailed subsurface mapping of the structure is hampered by the fact that geophysical data on the uppermost part of the crust exist mainly in the form of classified data from prospecting companies. Another unfortunate circumstance for a detailed understanding of the Roer Valley Graben is that geological, geophysical and, partly, geotechnical data are scattered over different national and regional organisations. Integration of the different data sets presently only exists within isolated projects and remains cumbersome for the graben region, especially across national borders.

The lack of, among others, a detailed model for the lower crust and upper mantle structure for the Roer Valley Graben, and a satisfying regional seismotectonic model which includes this graben, the so-called Belgian zone and the Rhenish Massif, means that some important questions remain unanswered. For example: Is there a crustal thinning associated with extension?

How do major faults observed at the surface continue at depth into the lower crust and what attitudes and relationships do they have? (Do faults extend with depth in a flower-like pattern? Does the Roer Valley Graben display asymmetric faulting comparable with the Rhine Graben?) Do shallow-focus earthquakes pose a serious threat? How do local seismic waves propagate and attenuate?

Of particular relevance for seismic hazard assessment, for example, are estimates of the seismic efficiency (i.e. the ratio between seismic and aseismic movement) and of the present neotectonic activity within the graben. These estimates are presently unattainable. The essential prerequisites for such analyses are accurate regional earthquake catalogues spanning long time intervals. Techniques in palaeoseismicity (the evidence of prehistoric coseismic deformation on faults and in adjacent terrains, e.g. palaeoslip and palaeoliquefaction), as known from more vigorously active seismic regions, are also being considered as useful tools. However, the Roer Valley Graben poses specific problems such as lack of significant topography (morphotectonic features, slope instabilities, etc.) that may assist in identifying the size and location of ancient earthquakes and thereby assist targeting of trenching and borehole investigative efforts.

The Roermond earthquake and its aftershocks

The Roermond earthquake on April 13, 1992, belongs with the Oslo Fjord earthquake of October 23, 1904, and the North Sea earthquake of June 7, 1931, to the largest earthquakes in north-western Europe in this century. The Roermond earthquake is a normal dip-slip event (dip 70° with respect to the horizontal plane, downthrowing to the west) with a moment magnitude $M_w = 5.4 \pm 0.1$, rupturing an area of about $10\text{--}15\text{ km}^2$ with an average slip of 20–30 cm. Stress drop is relatively small; the estimates remain uncertain, but somewhere between 4 and 9 MPa. A small foreshock, possibly indicating a more local asperity failure, occurred a few tenths of a second before the main shock. Studies of the many instrumental records for the main earthquake reveal some interesting features. The depth of about 17 km at which the rupture started, i.e. the hypocentre, appears relatively deep for this type of tectonic regime. Also, the fault dip of about 70° is relatively steep as compared to other crustal normal-fault dip-slip earthquakes world-wide. Most remarkable, however, is the aftershock distribution, which extends areally to as

much as 40 km to the south-east, i.e. towards Düren. More than 200 aftershocks occurred within two months after the main shock and a considerable number of them far to the south-east of the main shock epicentre. This distant aftershock activity is not easily explained as the product of postseismic static stress differences in the crust; alternative explanations seem to be required.

The ad-hoc joint international effort to install mobile seismograph stations and to co-ordinate the arrival time data was successful in recording and locating many of the aftershocks. These aftershocks have proved to be important for several purposes, among others: unambiguous determination of the main rupture plane, local site response studies, and the improvement of a local seismic velocity model.

The Roermond earthquake has stimulated several locally important practical actions:

- a. Because many different regional seismograph networks recorded the Roermond earthquake, the Observatories and Research Facilities for European Seismology (ORFEUS Data Center) initiated a compilation of the available seismograms, including format and seismograph system descriptions, on one CD-ROM disc. A similar action has been undertaken to gather waveform data for the larger aftershocks. Both datasets should permit the extraction of more detailed information on the aftershock distributions, their characteristics and the local velocity structure. In the future, regional network seismograms will be more easily accessible to a larger group of scientists due to newly-developed conversion programs and station descriptions.
- b. The Roermond earthquake has served as a ‘wake-up call’ for seismologists and engineers in the region. Although the region contains a relatively dense network of seismographs, the recording ability of this network proved to be inadequate for this large earthquake. This is because:
 - the dynamic range of many seismograph stations was insufficient to record the full (unclipped) waveform, and,
 - within a radius of more than 50 km, no strong motion recorders (accelerographs) were available to record ground acceleration.

The first aspect influences our capacity to recover detailed source parameters. The second aspect explains why the much needed real ground motion time series required for engineering safety and design purposes cannot yet be delivered.

Actions taken to meet these shortcomings include:

- installation of a broad-band high-dynamic range seismograph system in the Netherlands (station HGN near the ‘Heimansgroeve’) in 1994, and
- installation of accelerometers in Germany and in the Netherlands (planned).

Macroseismic observations, ground motion and site response

The Roermond earthquake was felt over an area of approximately $6 \times 10^5 \text{ km}^2$ and up to a distance of 450 km. In spite of their generally imprecise nature, macroseismic intensity observations are significant for depth estimates, engineering and hazard applications. The macroseismic data gathering for the Roermond earthquake shows, however, the lack of homogeneity between the different national questionnaires and the problems inherent in subjective intensity interpretations. These problems become obvious when different interpretations are deemed possible for the same observations. Accordingly, an appropriate homogeneous macroseismic questionnaire and prescribed interpretation techniques should be given a high priority by the working group of the Global Seismic Hazard Assessment Program (GSHAP) for Europe.

The available data do permit some definitive conclusions:

- significant damage occurred in the cities of Roermond and Heinsberg, but the hardest hit communities were villages such as Herkenbosch, Obenbruch and Dremmen.
- the maximum felt intensity was a little over MSK VII, but this should not be considered large. This maximum intensity is essentially due to the relatively large hypocentral depth. Smaller earthquakes at lesser depth may cause higher or comparable maximum intensities albeit over smaller areas.
- the local estimated damage, whilst large in monetary terms, should be considered moderate for this size of earthquake. With a few notable exceptions structural damage occurred mostly to older buildings and, remarkably, many churches over a considerable area. This last observation can be explained by the typical asymmetric structures of churches, with poor coupling between the tower and the body of the church. One implication is that older buildings seem to be hit harder by such earthquakes than modern buildings built according to existing codes. Consequently, improving building codes with respect to earthquake hazard will

have little effect, and greater emphasis should be placed on measures preventing or limiting damage to older existing structures. Macroseismic observations from the Roermond earthquake highlighted the well-known feature of local site amplifications of ground motion mainly in the range of $0.5 < T < 1 \text{ sec}$ ($T = \text{period of wave motion}$).

Significant amplifications in susceptible sediment bodies were not only observed in the epicentral area; restricted site amplifications were also reported in the Rhine valley between Köln and Koblenz, at distances up to 100 km from the epicentre. These observations are of crucial importance to the correct estimation of local site amplifications, and hence contribute to a major improvement of seismic hazard estimations for many areas in north-western Europe. Some of the papers describe small-scale projects that approach this problem using integrated geotechnical, geological and seismic data in both the Netherlands (Delft) and Belgium (Liège).

Ground motion amplifications at stations located in soft deposits in the east of Belgium and peak ground accelerations for a rock site on the edge of the Rhine Graben and on sediments within the Rhine Graben suggest that if strong motion records had been triggered in the near region of the epicentre, significant horizontal and vertical accelerations would have been documented. Assuming a focal depth of circa 17 km, the best fits of these few observations to empirical formulae suggests epicentral ground accelerations of ‘non-near field types’ to be circa 0.15 g. Higher local (amplified) accelerations may well have occurred.

Geotechnical and hydrogeological aspects

The Roermond earthquake triggered liquefaction at a number of localities both in the Netherlands and Germany. Regions with high vulnerability to liquefaction due to strong ground motion caused by earthquakes had earlier been identified in Limburg, the Netherlands, and were confirmed as such by this earthquake. The non-linear soil behaviour may have damaging effects on both buildings and dikes. Such extensive ground susceptibility provides opportunities for tracing palaeo-liquefaction effects, which can be the sole indicators of similarly large earthquakes before historically documented times. Both aspects are considered extensively in contributions from the Netherlands. In this country, earthquake hazard is included in models for flooding risk models and no significant revision of these models

seems to be warranted at present. However, liquefaction effects on traditional building foundations remain a matter of concern. Where practicable, the most realistic approach seems to be to avoid liquefaction-prone areas, but in densely built areas this may not be possible. Several papers contribute observations on ground settlement and foundation damage, attributed to the main shock. Much of the damage occurred locally, where loose sandy infills have been created over years of construction and landscaping. The most spectacular fissure injections and sand volcanoes occurred in the natural deposits of the floodplain of the river Roer at Herkenbosch in the Netherlands. Landslides (of any origin) are rare phenomena in the Netherlands; however, several slope-related instabilities in formerly-worked ground at the Brunsummerheide in Limburg have been identified as 1992 earthquake-induced features. A number of contributions describe investigations and the geotechnical processes involved in these rare ground failures.

Regarding groundwater aspects, the Regional Groundwater Information System (REGIS) has been suggested as a database for the future. An interesting observation that deserves wider attention is an increased radon content reported at a continuously monitored mineral spring water observation station in Bad-Brambach (Germany) directly after the Roermond earthquake. This should be considered as a secondary effect of the Roermond earthquake, possibly triggered by dynamic stress changes due to seismic waves passing the station. These observations may be significant with respect to the relevance of measuring radon content in spring water as an indicator for strain variations within the crust.

Seismic hazard and seismic risk

Seismic hazard analysis considers only strong ground motion. Seismic risk involves not only knowledge of this strong ground motion, but also consideration of the vulnerability and economic and social value of built structures. A consensus exists that the Roermond

earthquake confirms the established regional seismic hazard estimates, as based on a Poissonian model of the regional seismicity pattern. However, current seismic hazard analysis should be refined, particularly for nuclear facilities and other critical structures.

Seismic hazard assessment in low-seismicity areas, such as north-western Europe, generally has uncertainties because of the lack of available information on past seismicity. Therefore, reliable historical catalogues become of crucial importance. However, it requires a painstaking procedure to achieve reliable information in the Lower Rhine Embayment area. Also the need for palaeoseismic investigations is emphasised. Additional improvements could be obtained with a multi-disciplinary expert opinion procedure. The greatest improvements may well be obtained through microzonation and by evaluating local site responses throughout the region. Local site amplifications can have a significant hazard-increasing effect and this aspect has received insufficient attention to date in this seismic region.

Seismic risk values in the Roer Valley Graben and the adjacent Belgian region are appreciable, but are in general smaller than other natural risk factors, especially those of storms and floods. The total damage due to the Roermond earthquake was less than the damage due to a severe storm in the Netherlands. Moreover, storms have a significantly higher rate of recurrence than earthquakes of the size of the Roermond earthquake. This does not mean that larger earthquakes are of little economic concern, but an uninsured damage of more than 100 million ECU could be reduced easily by a number of simple considerations. Moreover, the large hypocentral depth and the 'favourable' time of occurrence (night time) were important factors contributing to a limited number of casualties. Shallower earthquakes at critical times in critical localities would have much greater impact. Practical engineering considerations, founded on an improved, more detailed, understanding of the seismogenic neotectonics of the region, will help to reduce the scale of future damage due to such earthquakes in this densely populated and highly industrialised part of Europe.