Open-pit mine design in seismic areas

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Dynamic effects from earthquakes can cause either total or partial failure of pit slopes as well as damage to important mining installations and liquefaction of waste heaps and tailings dams. Some form of dynamic analysis and design should, therefore, be considered.

Design of pit slopes against the effects of earthquakes is usually based on seismic hazard criteria as input to appropriate methods of stability analysis. Assessment of the seismic hazard depends mainly on economic and local safety considerations and less on such factors as the broader safety and environmental aspects that are currently used for other industrial and nuclear facilities. The criteria are usually quite well defined for such installations as nuclear power plants, large dams and oil refineries, but the relatively short operating life of an open-pit mine and the relatively low value of the raw materials that are mined need to be taken into consideration.

Two methods that are currently used in seismic hazard analysis are referred to as 'probabilistic' and 'deterministic'. The first gives results, in terms of the annual probability of occurrence or the return period, for a range of intensities, magnitudes or ground accelerations. Ground accelerations can be used directly in stability analyses for the design of slopes and mine geometry. Deterministic methods give only the largest possible intensity, magnitude or ground acceleration.

An increase in the volume of excavation that can result from a reduction in the slope angle to allow for seismic aspects leads to higher production costs and other similar economic consequences. The final decision on what is considered to be an acceptable level of risk should, therefore, be based on a cost–benefit analysis.

The proposed Arenas del Rey open-pit mine in southern Spain is presented as a case study in which these considerations and procedures have been applied and developed. Detailed seismic, geological and geotechnical investigations were carried out for the mine.

Arenas del Rey open-pit mine

The proposed Arenas del Rey mine is located in the Granada province of Spain (Fig. 1). It will extend over 6 km^2 and have a maximum depth of 270 m. The volume of the excavation is expected to total $\sim 400 \times 10^6$ m^3, total coal production being $\sim 40 \times 10^6$ t. The coal is destined for use in a power station and it is estimated that the operating life of the mine will be about 25 years.

Fig. 1 Site location

Geological situation

The Arenas area is within the Betic mountain range, which is an alpine chain that formed during the late Cretaceous period as a consequence of the subduction and collision phenomena of the Euro-Asiatic and African plates. At present, the plates are approaching at about 1.6 cm/year in the region of the Straits of Gibraltar and as a result of this movement neotectonic and seismic activity prevails in the region. Study of the regional tectonics shows large faults that cross the region in various directions, major east–west faults being the Negratin, Palomares and Alhama de Murcia and other, northwest–southeast, fault systems being those of Almeria and Padul (Fig. 2). Geological, geophysical and geomorphological data support the idea that a geotectonic interpretation of the region could be a series of crustal blocks, limited by these major fault systems.[1] The mine itself is situated in a Tertiary basin composed of sandstones, cemented sands and silts and lignites. The basin is surrounded by mountains.

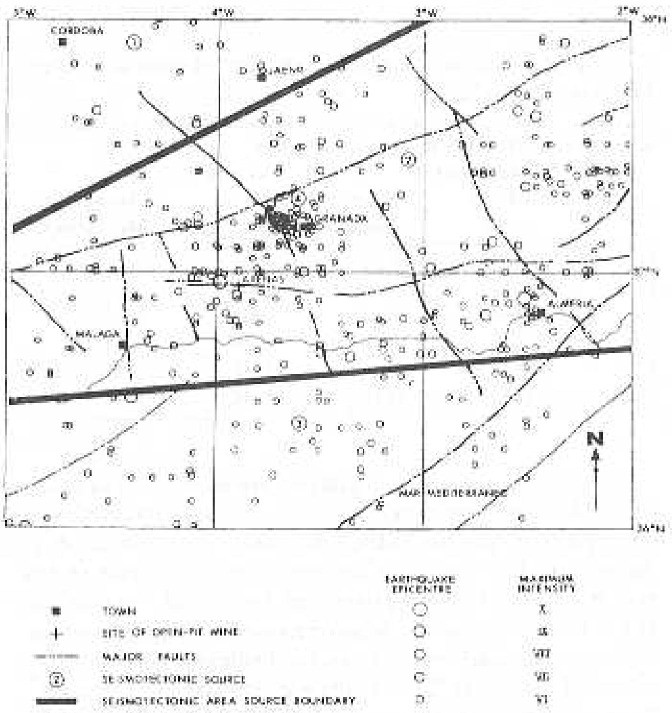

Fig. 2 Seismotectonic zoning

Evidence of active faulting in Arenas area

A detailed investigation of the area was carried out to identify surface faulting and other related features. Remote sensing, field geological and geomorphological surveys and gravimetric geophysical prospecting were used. As a result of these investigations a series of surface fault systems was identified (Fig. 3). The main system lies in an east–west direction, as was observed in the study of regional tectonics. It is a series of faults that defines a fracture zone about 4 km wide and more than 60 km long. The system could have been responsible for the Andalusian earthquake as well as many of the other earthquakes that have occurred in the area. Other systems were identified as lying in NNE–SSE and northeast–southwest directions. The fault systems are generally Quaternary and Recent. Surface rupture, as well as creep of the ground, has been identified in many parts of the region.

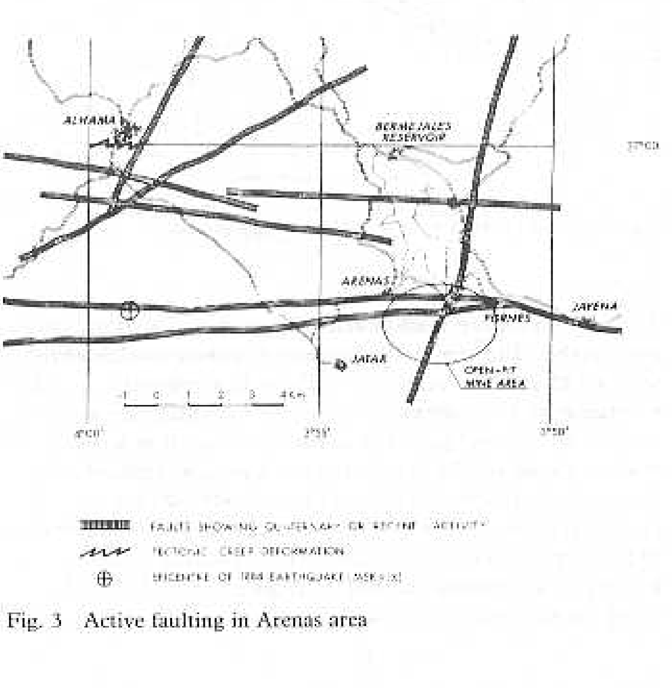

Fig. 3 Active faulting in Arenas area

Seismicity and seismotectonics

The mine is located in one of the most active seismic regions of the Iberian Peninsula. In historical times several large earthquakes of maximum intensities up to X on the MSK (Medvedev, Sponheuer and Karnik's) scale have occurred. In particular, the town of Arenas was destroyed by the Andalusian earthquake of 1884. That event, which had a maximum MSK intensity of IX, had its epicentre about 8 km from the site and caused not only severe damage and casualties but also landslides, liquefaction and other related phenomena.[2] Lists of the historical seismicity of the region were studied and over the last 2000 years 1186 events were identified in all; of these, 176 were identified as foreshocks or aftershocks, which left 1010 individual events. Examination of the homogeneity of this list resulted in a reduced data set of 486 events, the epicentres of which are shown in Fig. 2. The test of homogeneity was necessary because although most large events in the last 500 years or so have been described in historical records, only a few of the smaller events have been documented, so a biased data set is produced. As the present time is approached more and more of the smaller events are recorded. It was considered that whereas all the largest events (maximum intensities of IX or more) since 1300 had been recorded, only since 1950 had all the smaller events (maximum intensity of III) been recorded.

A seismotectonic map of the region has recently been produced,[3] on which active faulting, epicentres and geophysical information are shown. Some relationship between the tectonic situation and the seismicity of the region can be seen from this map. On the basis of this information a series of seismotectonic zones (Fig. 2) was considered appropriate for the analysis. In the northern part of the region a boundary between tectonic zones was identified between the Betic and Central Massif regions. A second boundary, dividing the landmass from the Alboran Sea, was also identified. The second boundary was not consistent with tectonic data, but was identified through considerations of seismicity. Historical records of earthquakes with epicentres situated offshore (e.g. in the Alboran Sea) are sparse, so if the offshore zone had been included with the onshore zone, which contains the site, the average seismicity around the site would have been reduced by the lack of offshore events and probably underestimated. In addition to the three zones, a point source of earthquakes was included in the area of Granada to account for the large concentrations of events recorded there. The concentration may well have been caused by bias introduced by the historical records of the large population centre, but in the absence of proof it was prudent to accept the less favourable possibility that some of the seismicity was concentrated close to the site.

Seismic hazard

Cornell's probabilistic method of analysis[4] was applied to the area shown in Fig. 2. The method accounts for the different earthquake distributions in the various specific seismic sources (zones and point sources), the attenuation of the seismic effects with distance and the focal depth of the earthquakes.

The seismicity in each of the seismic sources was produced from the homogeneous list in terms of the maximum intensity and the annual probability of this being exceeded. The data for the individual sources and the average relationship, used for all zones in the analysis, are shown in Fig. 4. It is assumed in the analysis that an earthquake can occur at any point in a seismic source with the same level of Poissonian probability. The attenuation law that was considered appropriate for the region includes focal depth effects and has the form[5,6]

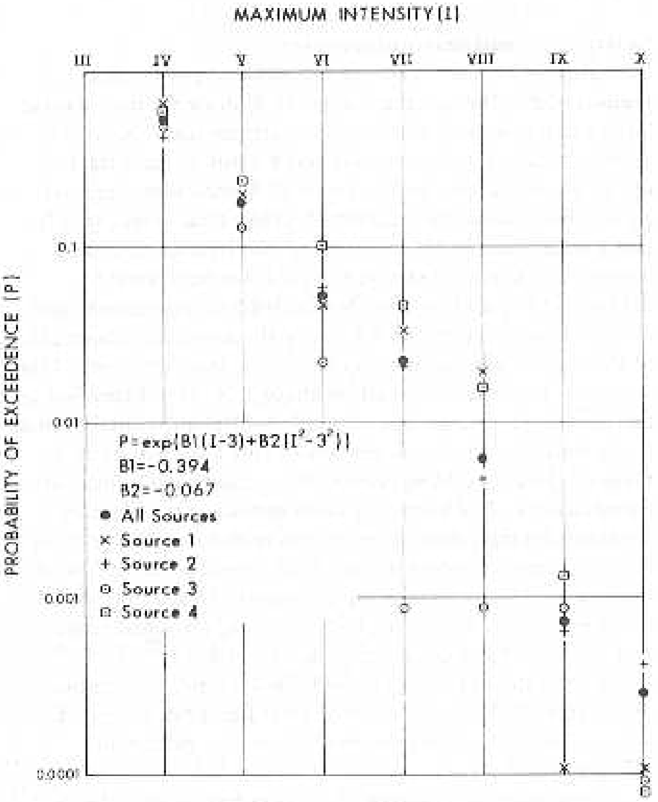

Fig. 4 Probability of exceedence against maximum intensity

$$I = I_o - a \log \frac{R}{h}$$

where I is intensity at the site, I_o is epicentral (maximum) intensity, R is distance to the focus, h is focal depth and a is a constant appropriate to each seismic source.

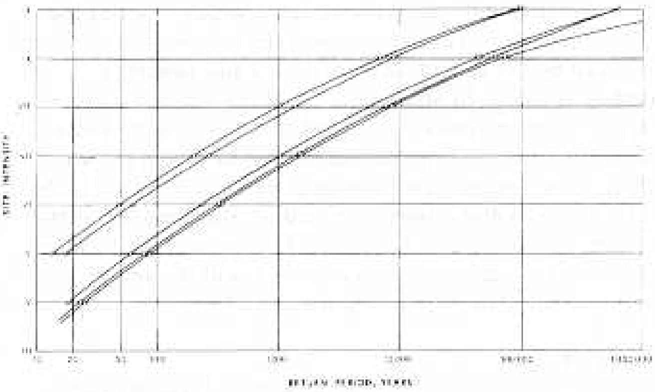

Fig. 5 Site intensity against return period

Table 1 Average and maximum intensities at Arenas del Rey mine site

Return period, years	Average intensity (MSK)	Maximum intensity (MSK)
10 000	VIII+	IX
1 000	VII	VIII
100	V−	VI+
50	V−	VI
20	IV	V+

Table 2 Ground acceleration–intensity relationships (after Trifunac and Brady[7])

Intensity	Maximum acceleration, g			
	Horizontal		Vertical	
	Mean	Standard deviation	Mean	Standard deviation
IV	0.02	0.01	0.01	0.01
V	0.03	0.03	0.02	0.01
VI	0.07	0.07	0.04	0.03
VII	0.13	0.06	0.08	0.04
VIII	0.26	0.09	0.17	0.10
IX	0.52	0.10	0.34	0.10

The results of a series of analyses are shown in Fig. 5, which illustrates the range of results that was obtained with different assumptions. Table 1 lists these results in terms of the average and maximum site intensities for various return periods. To assess appropriate peak horizontal and vertical ground accelerations the approximate relationship between intensity and acceleration given by Trifunac and Brady[7] was used (Table 2). The results are expressed in terms of the acceleration due to gravity, g, in Fig. 6, in which the maximum (maximum intensity coupled with mean relationship), the mean plus one standard deviation (average intensity coupled with mean plus one standard deviation relationship) and mean (average intensity coupled with mean relationship) are given.

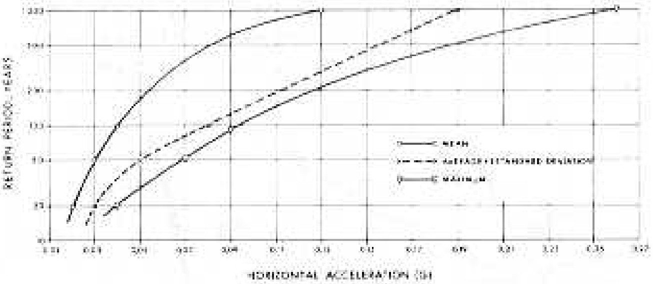

Fig. 6 Return period against horizontal acceleration

Design earthquakes

Three criteria were used to select appropriate design earthquakes. First, over the predicted operational life of the mine of 25 years an intensity of V can be expected according to the results of the probabilistic analysis. Second, as the coal from the mine will be used in a power station, a level of risk appropriate to a period of about ten times the operational life should be considered. An earthquake that produces a site intensity of VII corresponds to a return period of 250 years. It is interesting to note, however, that during the past 25 years an intensity of VII (from an earthquake included in the analysis) has been registered at the site. From Fig. 6 the horizontal ground acceleration appropriate to a return period of 250 years can be estimated as approximately 0.1*g*, with a vertical ground acceleration of approximately half this value (0.05*g*). Third, an additional peak condition, corresponding to a return period of 1000 years, was considered: this is equivalent to a site intensity of VIII with an appropriate horizontal ground acceleration of ~0.13*g*.

Slope design

A site investigation, which included appropriate laboratory tests, was carried out to assess the properties of the rock. Boreholes, geomorphological and geological mapping, well logging, seismic refraction profiles, cross-hole geophysics and pumping and packer tests were included. The representative properties of the materials are given in Table 3. The water-table was considered to be at half the depth of the excavation. This agreed generally with the hydrogeological data.

Table 3 Representative material types and geotechnical design properties

Material type	Dry density, kN/m³	Moisture content, %	ϕ' degrees	c' N/m²
Cemented sand (*A*1)	19	14	38–40	10
Cemented silt (*A*2)	18	18	35–37	80
Lignite (*B*1)	9–12	40	35	40
Clay (*B*2)	14	30	28	70
Marl (*C*)	15	26	40	200
Sandstone (*D*)	22	—	38	100

ϕ', effective angle of shear resistance; c', effective cohesion.

Selection of the appropriate method of slope stability analysis was affected by limitations on data quality. Specifically, geotechnical parameters were obtained mainly from mining boreholes, which were not particularly suitable for geotechnical purposes; extensive extrapolation of geotechnical information from a limited number of data was necessary; and most of the geotechnical investigation that was carried out for the open-pit mine was for feasibility purposes. (Mines are commonly excavated while only preliminary data are available, but subsequent geotechnical monitoring over the operational life of a mine allows a better definition of parameters and a progressively more detailed analysis of the situation.) These limitations rendered the use of a refined slope stability method inappropriate in that accurate, representative geotechnical parameters would be needed, and the more general, modified Bishop method was used. All analyses were in terms of effective stress. Dynamic input was included by introducing into each slice horizontal and vertical forces, each calculated as seismic acceleration times static weight.

The factors of safety that were judged accordingly to be required were for *static* conditions at least 1.3; for *average dynamic* conditions (i.e. a 250-year return period) at least 1.1; and for *peak dynamic* conditions (i.e. a 1000-year return period) at least 1.0.

Table 4 Slope angles from analysis

Slope type	Angle of final slope, degrees		Design slope angle, degrees
	Static analysis	Dynamic analysis	
1	36.0	33.8	33.0
2	35.5	33.0	33.0
3	31.0	26.0	26.0

The results of the analyses for three typical slopes, designated types (1), (2) and (3), are summarized in Table 4. A typical section through a slope of type (3) is presented as Fig. 7 and the relationship between seismic acceleration, slope angle and factor of safety is shown for the same slope in Fig. 8.

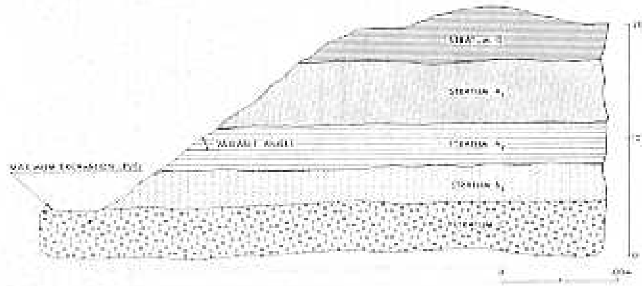

Fig. 7 Typical slope

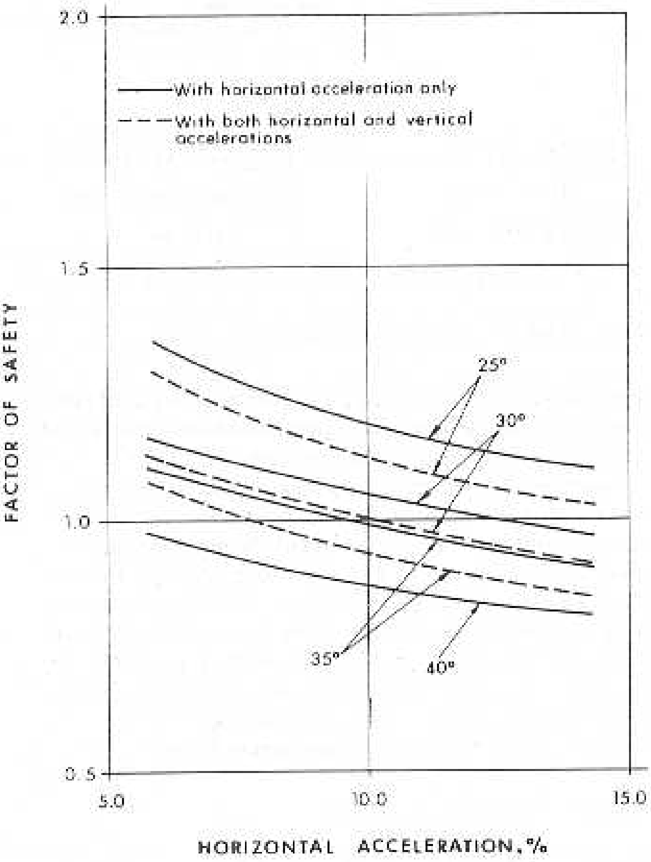

Fig. 8 Influence of seismic acceleration on slope of type shown in Fig. 7

Cost analysis

A complete cost analysis of seismic hazard for an open-pit mine is difficult because of the large number of uncertainties. Estimates, however, are made possible through the use of certain simplifications. Open-pit mines can be classified by two basic methods of working into those in which the working slope is exposed only temporarily and backfilling occurs as mining proceeds, i.e. in strip mining, and those which are not backfilled after exploitation. The Arenas mine was designed for strip mining and the method of exploitation is illustrated in Fig. 9.

The costs of implementing typical static and dynamic designs at Arenas del Rey are given in Table 5. The simplifications that were made for the purposes of cost

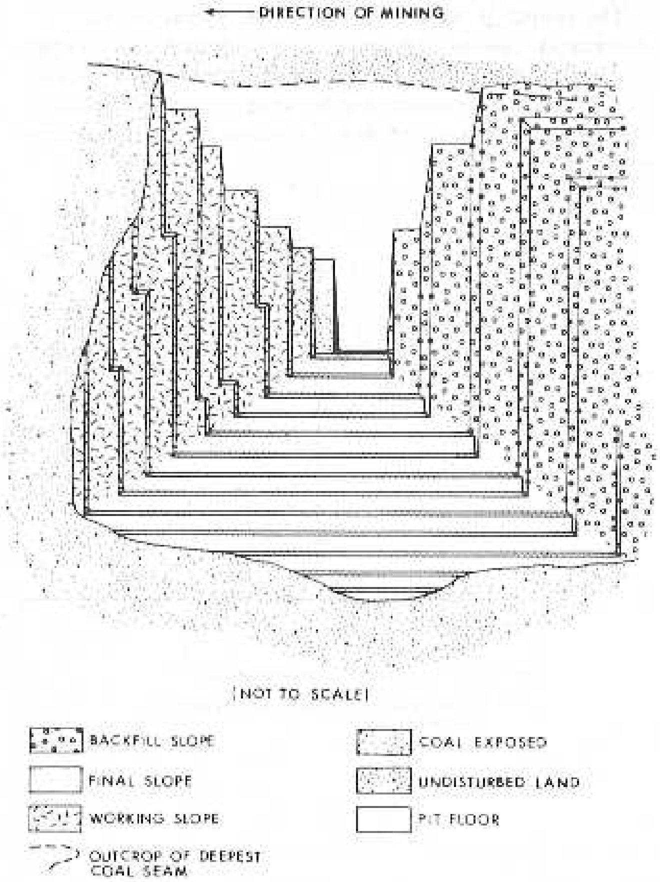

Fig. 9 Example of strip mining method

analysis were: (1) the assumption that during the life of the mine only one large earthquake, corresponding to the 250-year return period, would take place; (2) the assumption that with the strip-mining method only a section of the final slope (the face on which no further mining would take place) could fail through such an earthquake (conversely, if strip mining were not used, a final slope over a large proportion of the mine perimeter would be likely to fail); and (3) the basing of the costs of failure on the earthmoving operations that would be necessary to restore the failed slopes, an addition of 20% being the only allowance for other damage and no consideration being given to production losses.

Table 5 Cost analysis results

Design conditions	Average slope angle, degrees	Total spoil volume, 10^6 m^3	Cost, £10^6	Cost difference, £10^6
Static	34	411	380	—
Dynamic	25	467	427	47

The spoil volume that could slide as part of a slope failure if no dynamic design measures were adopted was estimated. A volume of 14.7×10^6 m^3, with an approximate restoration cost of £15 000 000, was estimated for strip mining. For failure of the final slope over a large part of the perimeter if the alternative mining method were employed the restoration cost could be £92 000 000. The cost of £47 000 000 for the additional operations that would be necessary to reduce the slope angle to dynamic requirements (Table 5) produced cost–benefit ratios of 0.32 and 1.96, respectively.

Discussion and conclusions

The example of the Arenas mine illustrates certain criteria that can be applied in a seismic design procedure for surface mining operations. The procedure consists of four main steps.

(1) The seismic hazard is evaluated by probabilistic methods to determine return periods for a range of ground accelerations or intensities at the site.

(2) Appropriate design earthquakes are selected for average and peak dynamic conditions. (*a*) For the average dynamic condition a return period equivalent to ten times the operational life of the mine is selected; the appropriate site intensity for this period is evaluated from the findings of step (1) and then either from this intensity or directly from step (1) values of the ground accelerations appropriate to the site are estimated. (*b*) For the peak dynamic condition the 1000-year return period earthquake and its corresponding accelerations are evaluated in the same manner as for the average condition.

(3) Appropriate slope stability analyses are performed and the pit slopes are designed for factors of safety of (*a*) not less than 1.3 in the static condition, (*b*) not less than 1.1 in the average dynamic condition and (*c*) not less than 1.0 in the peak dynamic condition.

(4) The acceptable level of risk for the mine is assessed by evaluating the influence of the slope design on the ratio of spoil volume to production volume and the related costs, estimating the cost if an appropriate earthquake takes place and causes a slope failure or other damage to the mine installation and evaluating the cost–benefit ratio.

The procedure requires tectonic, seismic, seismotectonic and geological studies. For Arenas much of the information was readily available, mainly from published works, but a detailed field survey was needed. The necessary geotechnical studies were similar to those for any slope stability analysis. When large mining areas are investigated, however, problems arise both in obtaining representative samples and in the selection of geotechnical parameters for design. Refined slope stability methods, such as finite-element analysis, can be used where the geotechnical data are of a quality compatible with the accuracy of the method. Simplified methods were appropriate at Arenas because of the great scatter and low quality of the geotechnical parameters.

The effects on the mine geometry of allowing for an earthquake hazard can include modification to the maximum width of the floor of the mine. It may also be necessary to alter the top benches of the slopes to avoid sharp edges and corners, which can cause local amplification of the surface waves that are caused by an earthquake and, hence, an increase in peak accelerations.

At Arenas the consequences of seismic design represented an increase in cost of approximately £47 000 000. When the open-pit was designed for the strip-mining method the cost–benefit ratio was evaluated as about 0.3, but had it been designed for the alternative method, the ratio could have been about 2.0.

A potential, related problem that affects surface mining is induced seismicity. Although earthquakes that are caused by this are usually only small, they may be of considerable importance in areas of low seismicity, and even in highly seismic areas a small earthquake close to the site can cause high accelerations.

As the final stage in the dynamic design, geotechnical and seismological monitoring and control during excavation are needed to ensure that the actual conditions are not too distant from those assumed for design.

It is concluded from the case study of Arenas del Rey that where there is a choice strip-mining methods might be appropriate for seismic areas: the hazard and consequent costs that must be ascribed to earthquakes may be much smaller than with other methods and the need for dynamic design can be avoided. In open-pit mines that are not backfilled after mining the cost–benefit ratios tend to support the need for a dynamic design. In the cost–benefit analysis only the costs of earthmoving were considered, but at some sites where costs that are incurred through failure of the slopes may be augmented by loss of life or damage to houses and industrial facilities, dynamic design could be necessary.

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