Development of a Risk Rating Matrix for Assessing Onshore Pipeline Geohazards

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An important aspect of the safe management of onshore buried oil and gas pipelines is the assessment and mitigation of risk. Ground movement is one of several causes of pipeline distress that is typically considered in failure analyses and may take many forms. A number of specific geological hazards may be considered, namely seismic effects, liquefaction, soluble rocks (karst), collapsible deposits, shrink/swell deposits, running sands, landslides and avalanches, hydrotechnics, erosion, mining, and construction activity. The causes and effects of different types of ground movement are not currently well differentiated in failure databases.

The main objective of this paper is to describe a risk rating matrix that allows the comparison of geohazards affecting transmission pipelines, including quantification of the likelihood, consequence and exposure of each geohazard. The methodology is intended to be applicable to significant lengths of pipeline or whole regions. A five-point quantitative scoring system for likelihood has been developed for each geohazard; the likelihood scores are then weighted by multiplication by an exposure rating (typically the proportion of the region exposed to the hazard for each likelihood rating) to take into account the variation of the geohazard over the region. The weighted likelihood scoring is then combined with a five-point consequence scoring system, taking into account economic, health and safety, loss of supply, reputational and environmental concerns. A single spider diagram is used to display the results of the risk analysis for each pipeline/geographical region. The paper also includes a review of current failure databases to provide data on the frequency of ground movement induced pipeline failures.

This paper describes the methodology and results of a UK study to identify sources of geohazard data, with a hypothetical example illustrating the use of the risk rating matrix, including the likelihood, exposure and consequence scoring elements. The approach allows the risk to buried pipelines from geological hazards to be quantified and for pipelines/geographical regions to be compared.

Keywords: Geohazard, risk rating matrix, likelihood score, consequence score, pipeline failure frequency.

Introduction

An important aspect of the safe management of onshore buried oil and gas pipelines is the assessment and mitigation of risk. Risk is typically expressed as the product of likelihood and consequence, and failure in this context is defined as damage to the pipe wall resulting in loss of product. Ground movement is one of several causes of pipeline distress that is typically considered in failure analyses. Ground movement may take many forms, including those caused by geological hazards (seismic activity and problematic geological deposits), geomorphological hazards due to gravity, erosion and water, and anthropomorphic (human-induced) hazards, such as mining and construction activity. The causes and effects of these different types of ground movement are not presently well differentiated in current failure databases.

On behalf of a group of gas companies, DNVGL have undertaken a programme of work to develop a more comprehensive geohazards knowledge base, detailing different types/forms of ground movement and “current best practices” and “emerging technologies” of prediction, analysis, instrumentation, mitigation and remediation.

The specific objectives of this paper are:

1. to discuss the types of ground movement that are hazardous to buried onshore gas/oil transmission pipelines;
2. to describe the development of a risk rating matrix to allow comparison of the likelihood and consequence of their occurrence;
3. to illustrate the risk rating matrix approach via a worked example applied to a theoretical case study.

In Section 2 the types of geohazard that may affect pipeline failure are discussed, and in Section 3 pipeline failure data from UKOPA and EGIG databases is reviewed. Then in Section 4 a method of assessing risks due to geohazards is proposed; the calculation of likelihood and consequence scores is described in Sections 5 and 6, respectively. Finally in Section 7 a hypothetical case study is described to illustrate the method of calculation.

Geohazards Categorisation for Pipelines

Ground movement is a diverse and complex subject, and may affect the integrity of gas/oil pipelines in a number of different ways. When considering pipeline failures due to ground movement, the current practice for pipeline failure databases is to record all geohazard related failures under the term ground movement. This approach ignores the type and cause of the geohazard which can be summarised as follows (Skipper, 2012):

- Geological Hazards (seismic activity and problematic geological deposits);
- Geomorphological Hazards (caused by gravity, erosion and water); and
- Anthropomorphic Hazards (human-induced).

The three general categories of geological hazard mentioned above can be further divided into a number of specific areas (see, for example (Rizkalla, 2008)), which are summarised in Table 1 and discussed in more detail below.

Table 1: Summary of geohazards relevant to pipeline failure

Geological category	***Specific geohazard***
Geological	Seismic
	Liquefaction
	Soluble rocks (karst)
	Collapsible deposits
	Shrink/swell deposits
	Running sands
Geomorphological	Landslides and avalanches
	Hydrotechnics (buoyancy, flooding)
	Erosion
Anthropomorphic	Mining
	Construction activity

Firstly, geological hazards comprise those caused by and related to seismic activity (e.g. earthquakes, volcanoes and tsunamis), and also those caused by geological deposits that may be variable, unstable, aggressive, or include large voids that could result in pipeline damage without the effect of any additional external action. Particular risks to pipelines are presented by displacement/shearing due to seismic-induced ground deformation, seismic vibration, ground liquefaction, soluble rocks, collapsible ground, expansive soils (shrink/swell) and running sands.

Secondly, there are several types of geomorphological hazard that may cause pipeline failure. Landslides refer to movements of rock or soil under gravity that may expose or damage a pipeline; snow avalanches are also included in this category. Hydrotechnics includes any effect of changing water levels on a pipeline, typically buoyancy and flooding, which may cause the pipeline itself to move or change the stress state around it. Erosion refers to the effect of wind and water on the natural environment and can take many different forms (e.g. river, coastal, wind etc.) which may be difficult to predict and map.

Thirdly, anthropomorphic hazards refer to those caused by human behaviour (but excluding direct third party damage). The specific hazards that will be considered in this category include mining and construction activity. Mining includes any form of mineral extraction, which may be opencast or underground. Ground movements induced by construction activity may include any building, engineering or development work that could change the ground conditions and induce movements and/or stress changes in local pipelines. Movements may come from many sources including: dewatering, tunnelling, piling, pipe moling, basement construction, cut/fill earthworks and above ground construction.

Review of Existing Failure Databases

The current UKOPA (United Kingdom Onshore Pipeline Operators' Association) and EGIG (European Gas Incident Data Group) transmission pipeline failure databases have been reviewed to assess the types and severity of ground movement hazards affecting pipeline operation (McConnell, 2014) (EGIG, 2015). Details of the databases are given in Table 2. In all cases, pipeline failure is basically defined as an incident resulting in an unintentional loss of product, and does not include other potentially serious "near miss" events, such as pipeline damage without rupture. The databases quantify events in failures per 1000km/year.

For the UKOPA database, 7 out of 191 failures were attributed to ground movement (4%). The UKOPA database does not provide a breakdown of types of ground movement.

For the EGIG database, over 100 ground movement failures (8% of total failures) have been recorded since 1970. The failure frequencies for external interference and construction defect/material failure are lower for the period 2009-2013 than for the full analysis period, whilst the failure frequency for ground movement has hardly changed, and is now equivalent to that for construction/material issues (see Table 3). It is perhaps therefore pertinent that more effort is being exerted now to address pipeline failures due to ground movement as these now represent a greater proportion of total failures.

Of the EGIG failures reported as ground movement, 85.2% of failures 2004-2013 (60.6% of failures 1970-2013) were attributed to landslides. Of the remainder, 7.4% (11.5%) failures were unknown, 3.7% (4.8%) were due to rivers and 3.7% (16.3%) were due to flooding. Failures prior to 2004 were also attributed to mining and dyke failure (3.8% and 1.0% of failures 1970-2013, respectively). No failures were attributable to seismic events or related hazards i.e. liquefaction, but this may be due to mitigation measures being successfully applied where seismic activity is likely. Neither was there reference to other geological hazards, such as soluble rocks, collapsible deposits or shrink/swell deposits.

Table 2: Summary of Pipeline Failure Databases

Database	*Full database name*	*Composition*	*Time period*	*Total length (current)*	*Total exposure*
UKOPA (McConnell, 2014)	United Kingdom Onshore Pipeline Operators' Association	Eleven UK pipeline operators	1962-2013	22,158 km	848,868 km.yr
EGIG (EGIG, 2015)	European Gas Pipeline Incident Data Group	Seventeen European gas companies	1970-2013	143,727 km	3,980,000 km.yr

Table 3: EGIG Primary failure frequencies by cause (EGIG, 2015)

Cause	*Primary failure frequency* *per 1000 km.yr*	
	1970-2013	2009-2013
External interference	0.156	0.044
Corrosion	0.055	0.042
Construction defect / material failure	0.055	0.026
Hot tap made by error	0.015	0.009
Ground movement	0.026	0.024

Development of a Risk Rating Matrix

In the UK, the gas industry is regulated and promoted by a number of statutory and industry-specific groups including the Health and Safety Executive (HSE) and Ofgem. The UK gas industry's professional institution, the Institute of Gas Engineer Managers (IGEM), have historically produced a number of Technical Standards, official approved codes of practice and guidance that are used to assist in compliance with national legislation, a range of which apply to the design and management of high pressure pipelines.

One such document, IGEM/TD/2, provides guidance for the risk assessment of "major accident hazard" pipelines containing natural gas (IGEM, 2013). A number of causal factors for pipeline failure are cited:

- External interference;
- Corrosion;
- Material and construction defects;
- Ground movement;
- Other causes, e.g. Fatigue.

The risk of ground movement is simply differentiated as being either 'natural', e.g. landslide, or 'man-made', e.g. excavation or mining. In order to understand the effect of such causal factors a failure frequency for each hazard is calculated.

The failure rate for natural ground movement and for man-made ground movement depends upon the susceptibility to landsliding or subsidence at a specific location. Failure rates for the causal factors cited in IGEM/TD/2 are based on published datasets held by industry bodies, e.g. UKOPA. UKOPA also commissioned a study to review the risk of transmission pipeline failure from landsliding. The results of that study showed that the primary factors influencing pipeline rupture rates were the landsliding rate, the pipeline wall thickness and the pipeline girth weld quality (with less severe leaks dependent on landsliding rate and wall thickness only). Landsliding rate or susceptibility was assessed using datasets made available by the British Geological Survey (GBS). Landslide incident rates are listed within IGEM/TD/2 and range between 0.5 and 0.005 per 1000 km year (IGEM, 2013). The codified advice for the prediction of failure frequency due to landsliding has been revised and reissued in June 2013 (Goodfellow, 2014).

Whilst IGEM/TD/2 provides an approach to assessing risk and calculating failure frequencies for landsliding, other geohazards are not dealt with in the same way. This is understandable, given that landslides represent the most significant geohazard to UK onshore pipelines in terms of recorded failures. However, a generic risk assessment method for a broader range of geohazards would provide a greater understanding of the assessment of risks to pipeline integrity, based on a more comprehensive range of criteria than failure frequencies alone. This approach would allow inclusion of other types of hazards that less frequently cause pipeline failure, thus taking account of the likelihood and the potential consequences of a wider range of risk factors. A detailed risk rating matrix is therefore proposed.

An additional advantage of a risk matrix approach is that it can be extended to allow the assessment and comparison of geohazards between geographical regions. A region may be defined in a number of ways, and the proposed methodology (described below) may be applicable to all these definitions. A region could be interpreted as a country, which may be useful for comparison and policy purposes. Where a country has considerably varying geology, then regions may be better defined by geological area rather than by geopolitical boundaries. Alternatively, the term region could be used to represent the route of a pipeline or section thereof. The facility to include geography-based variations in geohazards is a considerable advantage for very long pipeline assets, as it allows optimisation of monitoring, preventative and remedial measures to the areas where they would be of greatest benefit.

Risk is typically defined as the product of likelihood and consequence. In addition to the calculation of risk in terms of likelihood and consequence, it is pertinent to include an element of exposure to the geohazard within the risk score. Exposure refers to the proportion of a given pipeline or region that experiences a hazard at a particular intensity, so there will be a range of likelihood and exposure scores for a particular pipeline/region; this is explored in more detail in Section 7.

The magnitude or likelihood of a specific geohazard is typically defined by some form of zoned geographical map, such as earthquake or landslide zones. Such maps provide a basis for a likelihood scoring system that may then be used in the population of the risk rating matrix. However, such zoned geographical hazard maps are unsuitable for displaying multiple geohazards and also do not include provision for displaying the consequences of the hazard. In order to compare a range of hazards as a comprehensive risk rating matrix, it is proposed that a "spider" diagram is used, as this allows multiple variables and their magnitude to be displayed simultaneously. Each axis can be used to represent one type of geohazard. The score along the axis is determined by a combination of the likelihood of the hazard occurring, the proportion of the pipeline/region exposed to that hazard, and the possible consequence of that hazard in terms of pipeline failure. This combination results in the risk score for that geohazard. An example of a typical risk rating matrix is given in Figure 1.

In the following sections the likelihood and consequence scoring are discussed in more detail. Then in Section 7 a worked example of the risk rating is presented, pulling together the likelihood, consequence and exposure scoring.

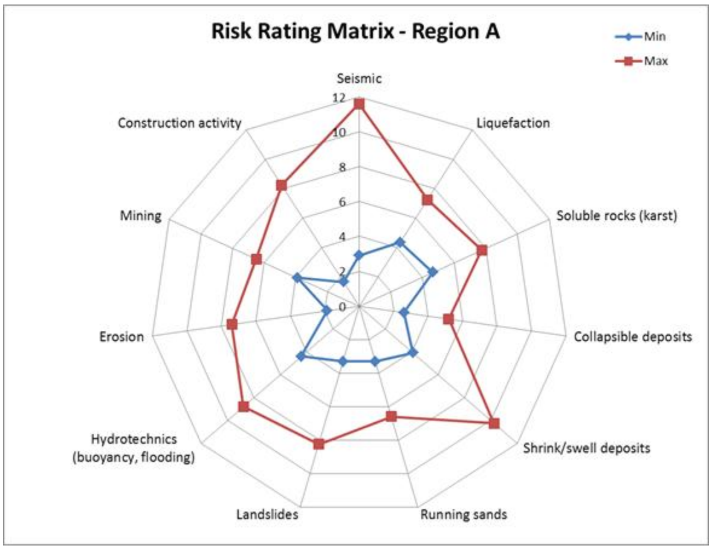

Figure 1: Typical risk rating matrix

Likelihood Scoring

The risk rating matrix is designed to be applied to a pipeline(s) extending over a large geographical area (e.g. one comprising several areas which may vary in geology/geohazard). To populate the risk rating matrix, relevant digital maps for the UK have therefore been sought to enable likelihood scores to be assigned for each geohazard listed in Table 1.

In the UK, a useful source of digital hazard maps is the British Geological Survey (BGS), in particular the "Geosure" datasets which combine digital maps with scientific and engineering reports for a number of geological hazards. The detailed digital data illustrated in the maps are available as attributed vector polygons and as raster grids. In addition, suitable categorisation of hazard ratings has been provided by BGS for several different types of geohazards (collapsible deposits, landslides, running sands, shrink-swell deposits and soluble rocks), and these have been used to form the basis of the likelihood scoring for the risk rating matrix for those hazards. Other sources of digital mapping include SHARE (Seismic Hazard Harmonization in Europe), The European Avalanches Warning Service, The Environment Agency, The Coal Authority, and Find Mapping Ltd (mineral extraction maps). It was found to be difficult to determine a suitable data source for ground movement effects due to construction activity as specific maps of construction activity (historic or current) are unavailable. For the purposes of this project, population density data has been used to develop likelihood scores, as low level construction activity is typically more prevalent in built up areas, but it is accepted that major construction projects, such as tunnels, airports, dams etc., will usually be away from centres of population, and alternative sources of data for mapping construction-induced ground movement should in future be sought.

In Table 4 below a system for likelihood scoring is proposed, with examples of score categorisation based on UK data; these could be adapted for use in other countries using relevant national datasets. Firstly, a generic qualitative likelihood scoring is proposed (shown at the top of the table), using a five-point system. Then, for each of these five categories, example maps and data have been used to develop a quantitative scoring system for each geohazard. It should be noted that in some cases a degree of engineering judgement has been applied to define the category boundaries, particularly where existing mapping does not define clear likelihood categories. It is also important to recognise that mapping alone may not fully determine the likelihood of a particular hazard at a given location, and that field investigations may play an important role in clarifying risk. However, the aim of this work is to provide a method of rapid risk estimation for reasonably large geographic areas which can then allow targeting of specific locations for detailed investigation, and for the application of mitigation measures and instrumentation. A benchmarking exercise may be a useful further stage of the project to hone the likelihood categorisations.

Consequence Scoring

Having considered the likelihood and exposure relating to a risk source, the consequence scoring is the final major component of the risk rating matrix. For this proposed risk rating matrix approach, a "universal" consequence scoring has been developed that can be applied to the consequences of any geohazard-related event, but is wholly independent of the causal factors. The proposed consequence scoring scheme is presented in Table 5. It is intended that the consequence of a hazard is scored in each of five categories (economic, health and safety, loss of supply, reputation and environment), and that the consequence score of a particular geohazard is defined by reference to the highest single score, rather than the average. This ensures that due importance is attached to the most severe sources of risk. For example, a gas pipeline failure that caused more than ten fatalities would score 5, even if the economic cost was low, there was little environmental damage, no loss of supply and only moderate effect on the owner/operator company's reputation. These five categories have been considered and approved by representatives from six European gas transmission companies, and are therefore considered to provide a robust consensus-based approach for the consequence scoring process.

Table 4: Proposed likelihood scoring system for UK geohazards

Geohazard	**Likelihood categorization origin(s)**	**A**	**B**	**C**	**D**	**E**
	Generic qualitative categorisation	***Extremely unlikely / not present***	***Very low possibility***	***Low possibility***	***Moderate possibility***	***High possibility***
Seismic	European Peak Ground Acceleration (European Seismic Hazard Map) (Anon., 2016a)	Peak Ground Acceleration 10% exceedance probability in 50 years				
		< 0.05	0.05 < 0.09	0.1 < 0.14	0.15 < 0.24	≥ 0.25
Liquefaction	European Peak Ground Acceleration (European Seismic Hazard Map) (Anon., 2016a) and *DNVGL Project team qualitative assessment*	Not present	Low susceptibility deposits, PGA <0.15	Low susceptibility deposits, PGA >0.15; or high susceptibility deposits, PGA < 0.15	High susceptibility deposits, PGA 0.15 < 0.25	High susceptibility deposits, PGA > 0.25
Soluble rocks	BGS Geosure (Anon., 2016b)	Present, but unlikely to cause problems, except in exceptional circumstances	Significant soluble rocks present, problems unlikely except with considerable water flow	Significant soluble rocks present, low possibility of localised issues if high water flow	Very significant soluble rocks present, moderate possibility of localised issues if concentrated water flow	Very significant soluble rocks present, high possibility of localised issues if concentrated water flow
Collapsible deposits	BGA Geosure (Anon., 2016b)	Note present	Unlikely to be present	Possibly present	Probably present	Have been identified
Shrink/swell deposits	BGS Geosure (Anon., 2016b)	Predominantly non-plastic	Predominantly low plasticity	Predominantly medium plasticity	Predominantly high plasticity	Predominantly very high plasticity
Running sand	BGS Geosure (Anon., 2016b)	No indicators	Slight potential with water table rise	Possibility if major changes in ground conditions	Significant potential with relatively small changes in ground conditions	Very significant potential
Landslides	BGS Geosure (Anon., 2016b)	No indicators	Unlikely to be present	Possibility if major changes in ground conditions*	Significant potential with relatively small changes in ground conditions*	Very significant potential; active or inactive landslide may be present
	European Avalanche Warning Services (Anon., 2016c)	Snowpack well bonded; triggering of small avalanches only possible with high additional loads** on isolated very steep, extreme terrain	Snowpack moderately well-bonded; triggering possible with high additional loads** on steep slopes	Snowpack moderately to poorly bonded; triggering possible with low additional loads** on steep slopes; some medium, occasional large avalanches	Snowpack poorly bonded; triggering likely from low additional loads**; numerous medium-sized and often large-sized avalanches expected	Snowpack poorly bonded and largely unstable; numerous large-sized and often very large-sized avalanches expected

Geohazard	**Likelihood categorization origin(s)**	**A**	**B**	**C**	**D**	**E**
Hydrotechnics (buoyancy, flooding)	Environment Agency Flood Map for Planning (Rivers and Sea) (Anon., 2016d)	Not at risk (Flood Zone 1 – Low Probability)	Unlikely due to flood defences (Flood Zone 1)	Flood Zone 2 – medium probability	Flood Zone 3a – high probability	Flood Zone 3b – functional floodplain
	BGS groundwater flood susceptibility data (Anon., 2016e)	Not at risk	Not at risk, except in exceptional circumstances	Limited potential for flooding	Potential for flooding below ground level	Potential for surface flooding
Erosion	Coastal – Environment Agency Coastal Erosion Map (Anon., 2016f), and Flood Map for Planning (Rivers and Sea) (Anon., 2016d)	No coast	Actively managed sea defences, Flood Zone 1	Actively managed sea defences, Flood Zone 2 or 3	'No active intervention' but no erosion expected	'No active intervention' with predicted erosion rate, or 'managed realignment'
	River - *DNV GL Project team*	Not adjacent to river	Adjacent to stream	Adjacent to medium river, or under stream	Adjacent to large river, or under medium river	Under large river
	Surface water flooding - Environment Agency Flood Map for Planning (Rivers and Sea) (Anon., 2016d)	Not at risk (Flood Zone 1 – Low Probability)	Unlikely due to flood defences (Flood Zone 1)	Flood Zone 2 – medium probability	Flood Zone 3a – high probability	Flood Zone 3b – functional floodplain
	Overland flow - *DNV GL Project team*	Extremely unlikely to experience overland flow	Low erosion risk surface, low overland, flows	High erosion risk surface, low overland flow	Low erosion risk surface, known to be subject to high overland flow	High erosion risk surface, known to be subject to high overland flow
Mining	Findmap Areas of Potential Underground Mining, and Areas of Potential Coal Mining (Anon., 2016g)	No mineable minerals present	Minerals present, unlikely to be mined	Minerals present, potentially mined area	Minerals have historically been mined	Minerals currently being mined
Construction activity	European Commission Eurostat data (Anon., 2016h)	inhabitants per square km				
		< 50	50 to 100	100 to 135	135 to 170	> 170

* Change in ground conditions is defined, for this project, as a change in any of the following: groundwater level, mining activity, construction activity (adjacent buildings, change of slope profile, change of drainage conditions), dissolution of soluble rocks, chemical changes to soil.

** High additional loads are defined as two or more skiers/snowboarders without good spacing; snowmachine; explosives; single hiker/climber. Low additional loads are defined as individual skier/snowboarder riding softly; snowshoer; group with good distances.

Table 5: Proposed consequence scoring scheme for UK geohazards

Consequence	**1**	**2**	**3**	**4**	**5**
Economic (total costs including repair, remediation and compensation)	<€100K	€100K to €1M	€1M to €10M	€10M to €100M	>€100M
Health and Safety	None or minor injuries	Injuries requiring hospitalization or over seven-day incapacitation	One fatality	Two to ten fatalities	> Ten fatalities
Loss of supply	Planned short-term interruption to domestic customers to facilitate repair	Planned interruption to large industrial or priority consumers (hospitals etc.); or medium-term or repeated interruption to domestic customers	Sudden interruption to large industrial or priority consumers (hospitals etc.); or sudden and sustained interruption to domestic customers	Sudden and sustained interruption to large industrial consumers or priority consumers (hospitals etc.)	Major loss of supply to all or part of a major city or region
Reputation	Occasional one-off negative media attention; local community impacts and concern	Negative media attention (days); sectional community impacts and dissatisfaction; ministerial concern	Consistent negative media attention (weeks); considerable and prolonged community impact and dissatisfaction; ministerial intervention	Consistent extreme negative media attention; significant adverse community impact and condemnation; public government intervention	Irreparable reputational damage, threatening company existence
Environment	Minor harm (e.g. noise complaint) or temporary harm (e.g. small area of contamination)	Moderate short-term damage on a local scale	Extensive short-term damage or moderate long-term damage on a local scale	Extensive long-term damage on a local scale	Extensive long-term damage on a regional scale

Risk Rating Matrix Scoring System: Example Case Study

As previously discussed, the risk rating matrix scoring system is based on a combination of likelihood and consequence scoring, with an allowance for the exposure of the region/pipeline to each geohazard. In order to explain this scoring system more fully, a hypothetical case study is presented below, based on a single pipeline crossing through a region with varying geohazard potential.

Likelihood scoring

For each geohazard, the likelihood scoring section has been divided into five categories (A to E), in accordance with the five categories proposed in Table 4. Then each of these categories has been scored according to the proportion of the pipeline that falls within each characteristic sub-region (.i.e. the exposure component). The likelihood scores are then weighted according to the likelihood category, to account for the increasing probability of occurrence, such that the score for Category A carries a weighting factor of 1, and Category E carries a weighting factor of 5.

To illustrate this, consider Region X and the risk to a specific pipeline due to seismicity in that region. Figure 2 shows graphically that Region X has been mapped to have three levels of seismic likelihood within its boundaries (B, C and D). After plotting the pipeline over the likelihood map it was determined that:

- 20% of the pipeline lay in the sub-region with a likelihood rating B (10% exceedance probability of 0.05 to 0.1 Peak Ground Acceleration (PGA) in 50 years) and thus an exposure rating of 0.2 is applied
- 70% of the pipeline lay in the sub-region with a likelihood rating C (10% exceedance probability of 0.1 to 0.15 PGA in 50 years) and thus an exposure rating of 0.7 is applied
- 10% of the pipeline lay in the sub-region with a likelihood rating D (10% exceedance probability of 0.15 to 0.25 PGA in 50 years) and thus an exposure rating of 0.1 is applied

Hence in Table 6, for the seismic hazard row, exposure values of 0.2, 0.7 and 0.1 have been entered under Categories B, C and D respectively. A similar exercise is then undertaken for all other hazards using appropriate mapping and pipeline overlays to get the respective percentage estimates.

The method may also be applied to assess the risk to, for example, a network comprising several pipelines in a single region. In this case, a laborious exercise could be undertaken to assess every pipeline as above and to then sum the lengths in each likelihood sub-region for the whole network. Alternatively, the total area of each sub-region across the whole network could be measured and this could be used as an approximation for the exposure values for the whole network. This second approach is more applicable to networks where the distribution of all of the individual pipelines is largely uniform across all sub-regions.

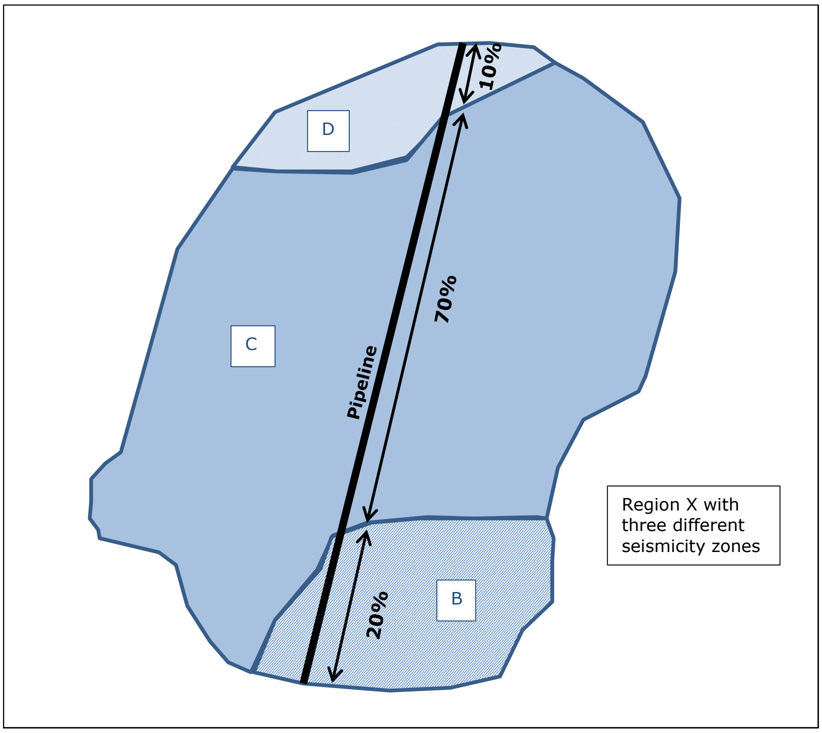

Figure 2: Example of exposure scoring for Region X seismicity

Consequence scoring

Having scored the likelihood for a pipeline or region, the next step is to score the consequence. The consequence scoring process is not straightforward as it comprises factors which cannot be accurately quantified to a single basis (e.g. cost). The assessment will require judgement to be applied to give a maximum and minimum value for each consequence type based on the likely extremes of damage caused by each ground movement type as described in Table 5, and then determine the overall maximum and minimum values across all categories of consequence.

To illustrate this, again consider Region X and the risk to a specific pipeline due to seismicity in that region, and make the following assumptions in the assessment of the consequences:

- Economic consequence ranged from 2 to 4
- Health and safety consequence ranged from 1 to 3
- Loss of supply consequence ranged from 3 to 4
- Reputation consequence ranged from 2 to 4
- Environmental consequence ranged from 1 to 3

Over all of the consequence categories, the assessed score ranged from 1 to 4, hence in Table 6 the minimum and maximum values have been entered as 1 and 4. A similar exercise would need to be undertaken for all hazard types for the pipeline, or for the region as a whole if a network of pipelines were to be assessed.

Risk scoring

Having determined the likelihood and consequence scores, the range for the risk score is then determined by multiplying the weighted likelihood scores by the consequence score:

$$\text{Risk} = (1A + 2B + 3C + 4D + 5E) \times \text{Consequence}$$

Using seismic activity as the ground movement type from Table 6 as a worked example again:

$$\text{Risk}_{min} = [(2\text{x}0.2)+(3\text{x}0.7)+(4\text{x}0.1)] \times 1 = 2.9$$

$$\text{Risk}_{max} = [(2\text{x}0.2)+(3\text{x}0.7)+(4\text{x}0.1)] \times 4 = 11.6$$

If desired, in addition to minimum and maximum risk calculations, the 'average' risk could also be estimated following the same approach. Care would need to be taken to define what 'average' would mean of course. A similar calculation is then undertaken for all hazards, and Table 6 completed accordingly. Based on the completed table, the Risk Rating Matrix shown in Figure 1 would then be plotted for Region X. This shows visually that seismic risk is the dominant risk, and that there are high risks too from shrink / swell deposits and geochemical attack. Mining and collapsible deposit risks are the lowest.

Table 6: Risk scoring example, Region X, seismic area

Ground movement type	**Likelihood**					**Consequence**		**Risk**	
	A	B	C	D	E	Min	Max	Min	Max
Seismic		0.2	0.7	0.1		1	4	2.9	11.6
Liquefaction	0.75	0.1	0.1	0.05		3	5	4.35	7.25
Soluble rocks (karst)	0.75	0.1	0.05	0.05	0.05	3	5	4.65	7.75
Collapsible deposits	0.9		0.05		0.05	2	4	2.6	5.2
Shrink/swell deposits	0.4	0.35	0.1	0.1	0.05	2	5	4.1	10.25
Running sands	0.7	0.1	0.1	0.05	0.05	2	4	3.3	6.6
Landslides	0.65	0.2	0.05	0.05	0.05	2	5	3.3	8.25
Hydrotechnics (buoyancy, flooding)	0.4	0.3	0.1	0.1	0.1	2	4	4.4	8.8
Erosion	0.7	0.2	0.1	0.05	0.05	1	4	1.85	7.4
Mining	0.9		0.05		0.05	3	5	3.9	6.5
Construction activity	0.7	0.1	0.1	0.05	0.05	1	5	1.65	8.25

Conclusions

This research set out to provide a framework for assessing the risk to onshore buried pipelines from geohazards. The following conclusions can be drawn:

- Various geohazards that may present a risk of failure to buried onshore pipelines have been identified and classified.
- A visual method of displaying the likelihood and consequence of each geohazard has been developed – the risk rating matrix. This allows the risk to buried pipelines from geological hazards to be quantified and for pipelines/geographical regions to be compared.
- Generic and specific scoring systems have been developed for the likelihood of each geohazard occurring in a given region, based on available UK digital geohazard maps and other data.
- A weighted exposure scoring scheme is proposed to take account of variations in geohazard intensity along the length of a pipeline or region.
- A generic consequence scoring system for all geohazards has been proposed, based on economic, health and safety, loss of supply, reputational and environmental factors.
- A hypothetical case study has been presented, demonstrating the application of the risk rating matrix approach and its versatility in taking into account to the proposed likelihood, exposure and consequence scoring schemes, to give an assessment of the pipeline risk due to geohazards and the variations in risk along its length.

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