Seismic Hazard to Welded Steel Pipelines in the United Kingdom

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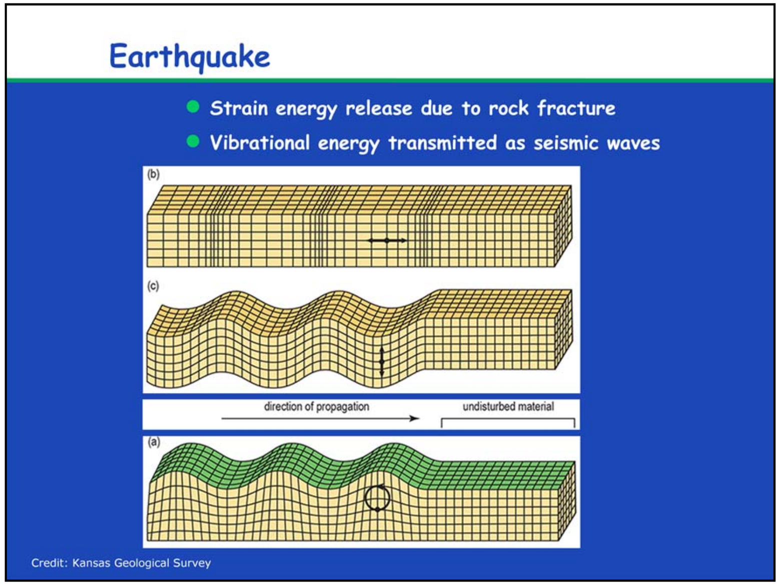
Work motivated by the potential need for UKOPA to produce guidance on seismic design requirements in the UK for onshore pipelines and installations. Eurocode 8 now provides requirements for the seismic design of a wide range of structures in Europe. The decisions on application of the code in the UK are set out in national annexes and a BSI published document. The current UK stance is that certain structures will warrant a consideration of seismic actions. The current work was commissioned to review pipeline code requirements in the UK for seismic design and to examine the justification for some UK structures to be designed for seismic actions. Also, to review policy development initiated by National Grid.

Overview

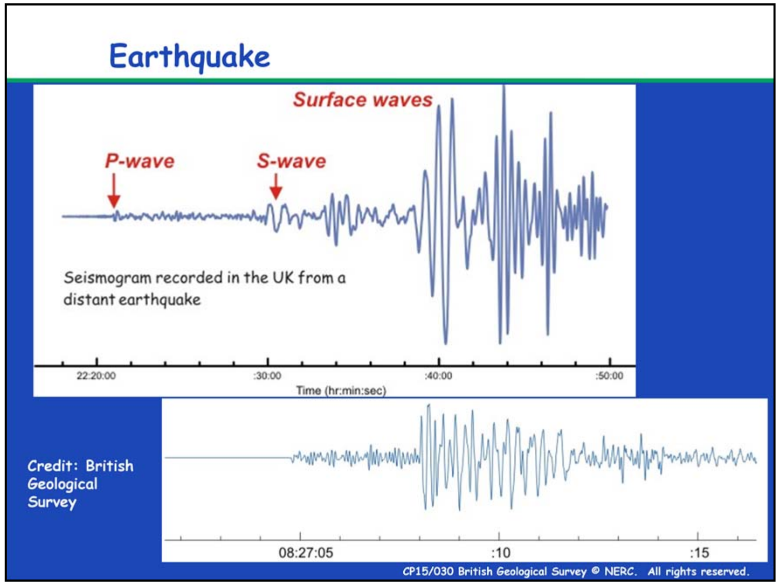
- Earthquakes
- Magnitude & Intensity
- UK Seismicity
- UK Seismic Hazard Studies
- Eurocode 8
- UK Seismic Design Requirements
- Pipeline Codes
- Return Periods
- Seismic Hazard to Pipelines & Installations
- Seismic Hazard & Vulnerability
- Seismic Screening
- National Grid Policy Development
- Recommendations



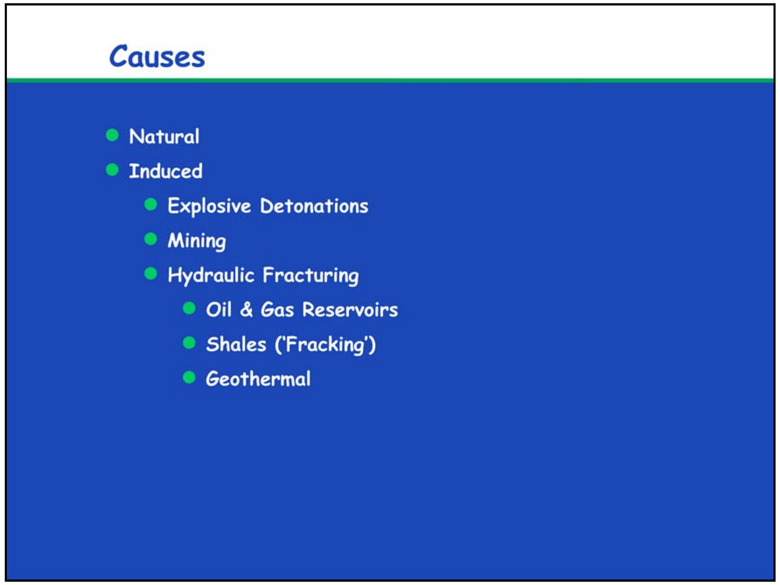
Primary waves P-waves – compressional - fastest

Secondary waves S-waves – shear – half the speed of P-waves

Surface waves – compound – slightly slower than S-waves



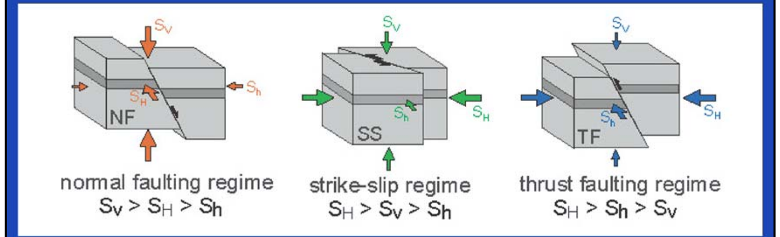
Bottom seismogram is for a 2.9 M_L earthquake near Dumfries in May 2001.



Causes of seismic waves.

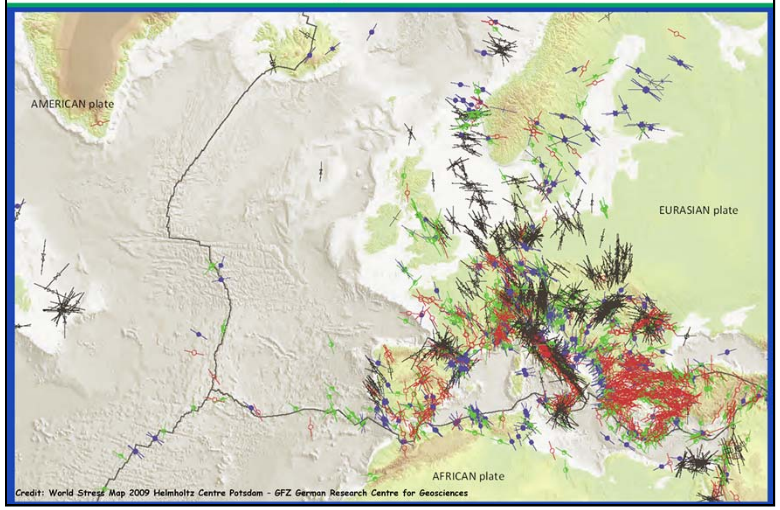
Geological Faults

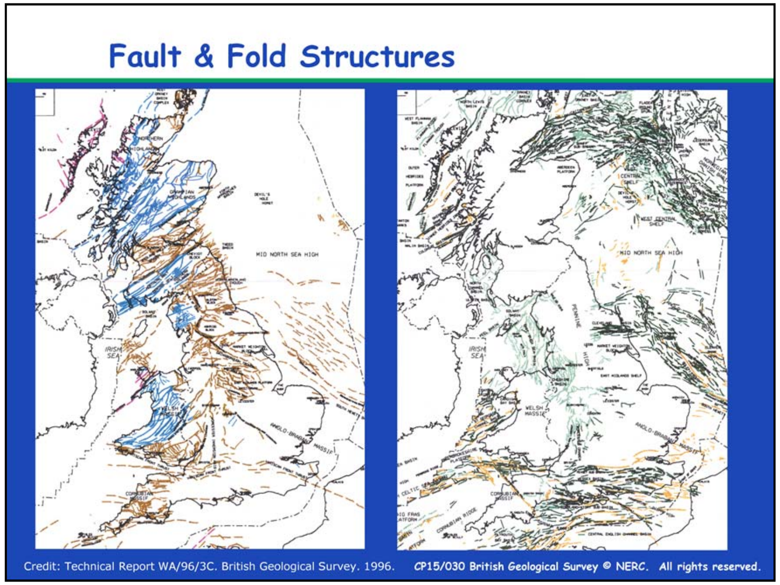
Geological Faults



Credit: World Stress Map 2009 Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences

Tectonic Setting





Precambrian >534 mya - magenta

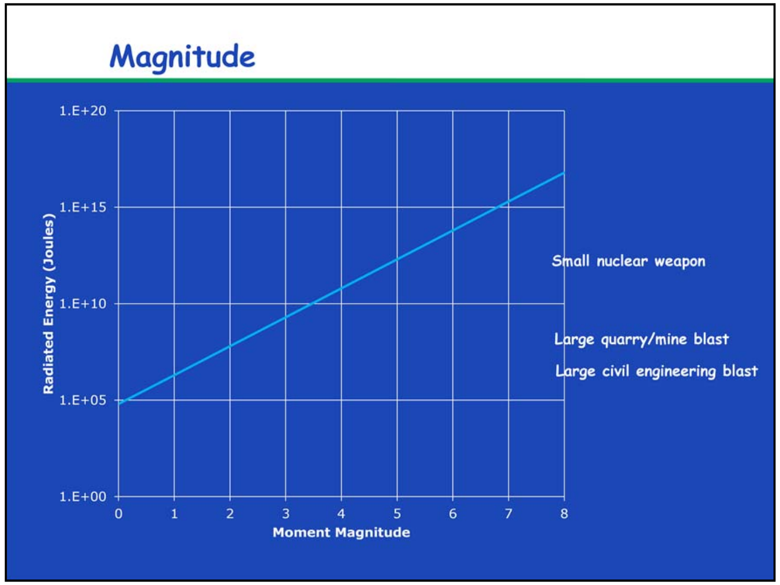
Early Palaeozoic structures ~500 mya (Grampian orogeny) & ~400 mya (Caledonian orogeny) – blue

Late Palaeozoic structures ~300 mya (Variscan orogeny) – brown

Permo-Triassic structures ~200-300 mya (extensional basin development) – pale green

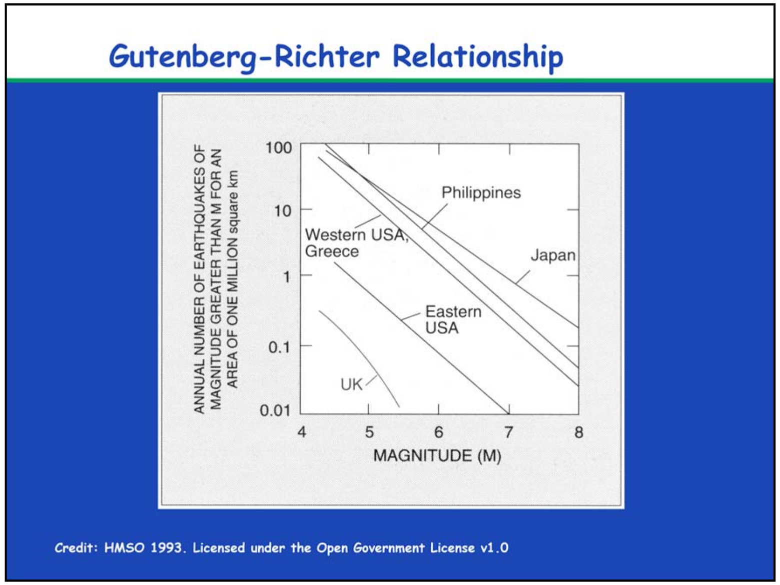
Jurassic/early Cretaceous structures ~100-200 mya (extensional) – dark green

Cenozoic structures <65 mya (Alpine orogeny) - orange



UK seismograph network should detect events of magnitude 1.5 and larger in mainland Britain. ~100 events detected annually.

Each magnitude increase corresponds to a ~32 fold increase in radiated energy.



GB ~0.23 milion km^2

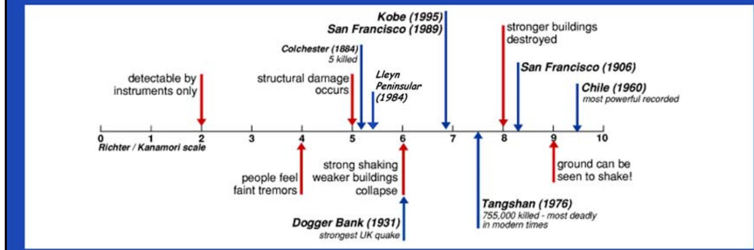
Magnitude 3.7 or larger every year

Magnitude 4.7 or larger every 10 years

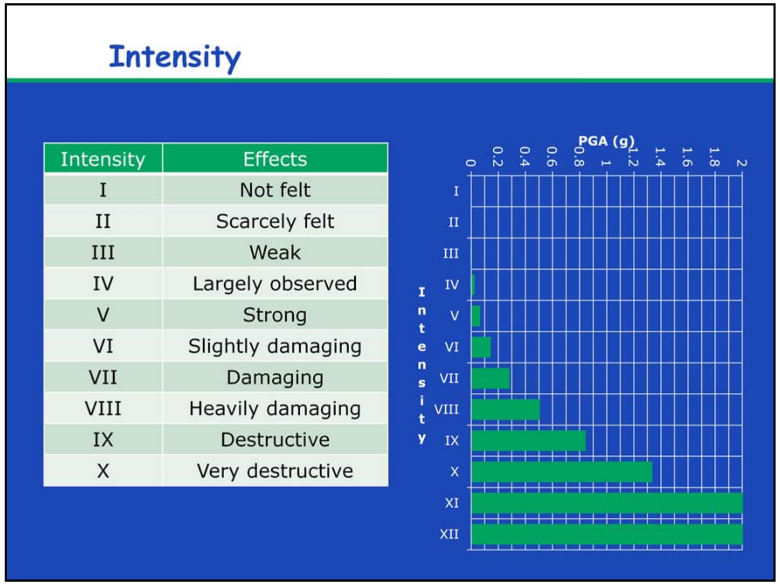
Magnitude 5.6 or larger every 100 years

Maximum Magnitudes

- Natural 5.5-6.5
- Induced
  - Mining 3.2-3.5
  - Explosive Detonations 1.0-2.0
  - Hydraulic Fracturing 1.9-3.0



Credit: St Vincent College



In 1989 a magnitude 5.6 M_l earthquake at a focal depth of ~11.5 km occurred at Newcastle in Australia producing a maximum intensity of VIII. There were 13 deaths, at least 150 injuries and ten of thousands of damaged buildings.

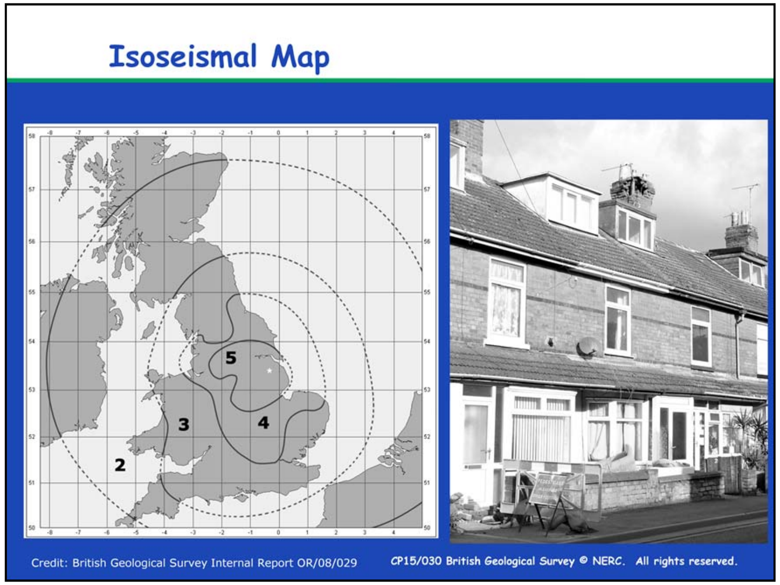
VI Non-structural damage

VII On-set of structural damage to ordinary well-built structures (small cracks), considerable damage to poorly built or designed structures (large cracks).

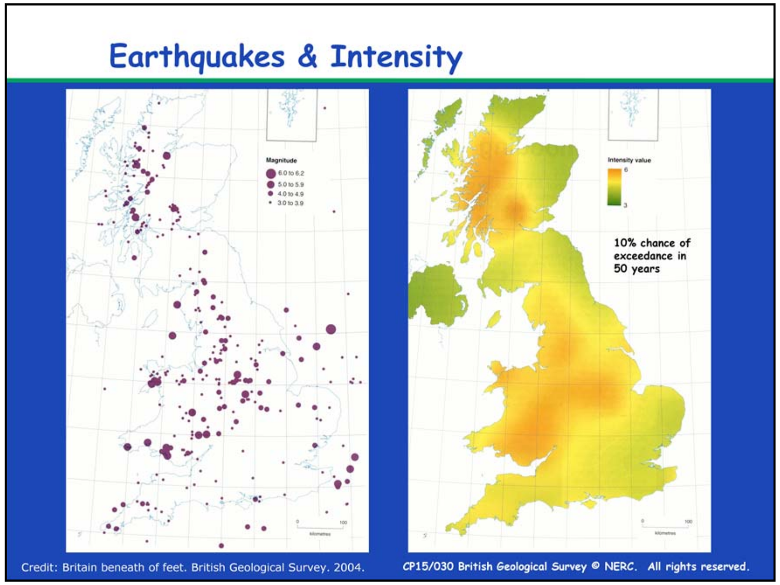
VIII Considerable damage to some ordinary well-built structures (partial collapse). Some weak older structures may collapse.

IX Considerable damage to specially designed structures. Partial collapse of substantial buildings. Some well-built buildings collapse. Many weak structures collapse.

X Many ordinary well-built buildings collapse. Rails buckle. Large landslides.



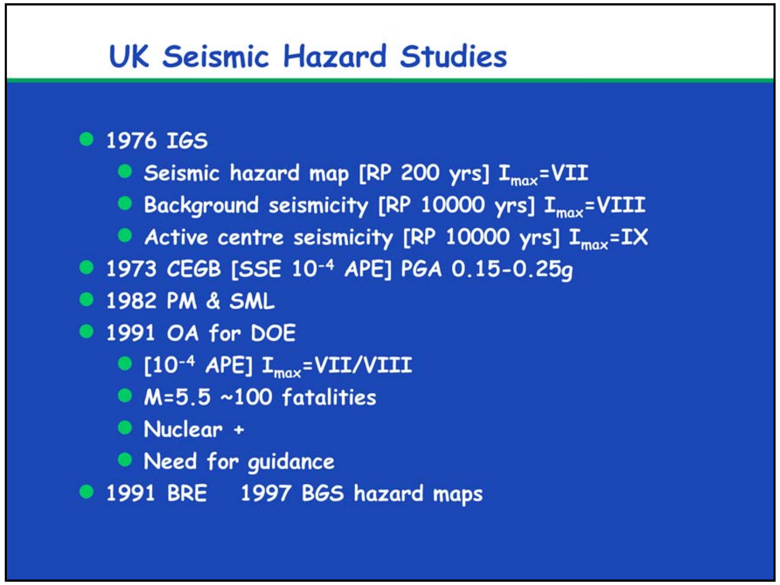
Market Rasen earthquake of February 2006. Local magnitude 5.2. Cost to insurance industry of low ten of millions. Photograph taken at Gainsborough (~30km west of Market Rasen).



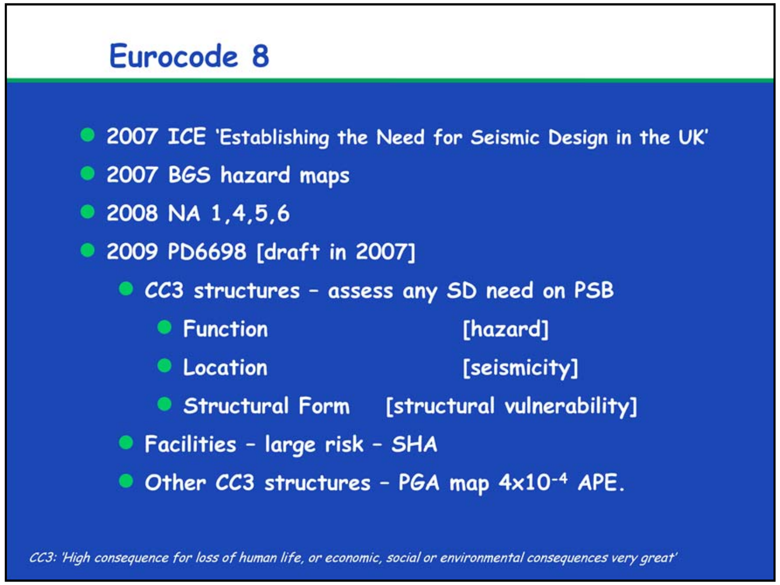
Threshold magnitude of engineering significance is ~4.5. There have been ~27 earthquakes across the UK of this magnitude or greater in last 300 years.

Threshold intensity of engineering significance is ~VII.

Kessock Bridge is one of the earliest examples of a civil engineering structure in the UK to incorporate seismic resistance into the structural design. The bridge incorporates seismic buffers at the north abutment. The bridge crosses the line of the Great Glen Fault to the north of Inverness. Construction started in 1976 and was completed in 1982. Design took place in the early 1970's and probably contributed to a motivation for more research on UK seismicity at the Institute of Geological Sciences.



Nuclear + may include some fuel and chemical installations, dams and unusual structures (sports arenas, tall chimneys).



Study for ICE commissioned in December 2006, report issue 1 completed in 2007, report issue 2 completed in January 2008.

BGS study started in 2007, meeting at ICE in April 2007 with industry experts, report issue 1 completed in September 2007, report issue 3 completed January 2008.

NA to Part 2 (bridges) published in 2009.

BS EN 1998-1:2004 General rules, seismic actions and rules for buildings

BS EN 1998-2:2005 Bridges

BE EN 1998-3:2005 Assessment and retrofitting of buildings

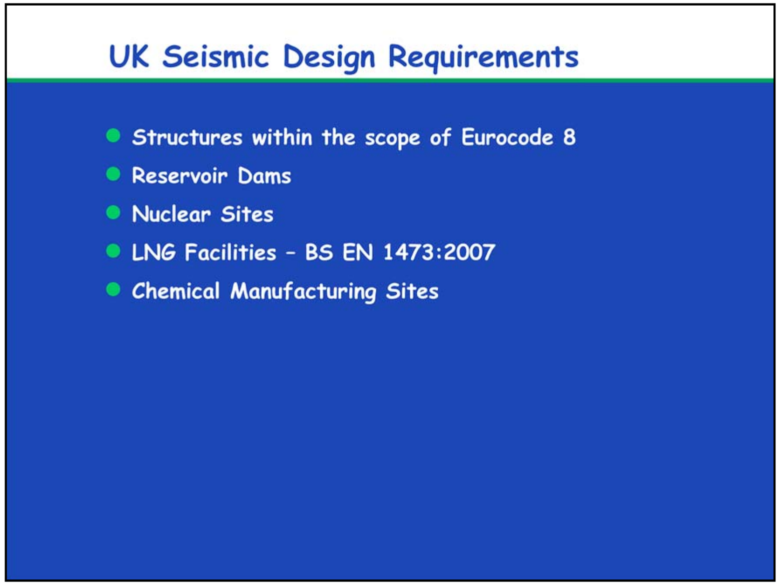
BS EN 1998-4:2006 Silos, tanks and pipelines

BS EN 1998-5:2004 Foundations, retaining structures and geotechnical aspects

BS EN 1998-6:2005 Towers, masts and chimneys

CC3 structures defined in BS EN 1990:2002 as 'High consequence for loss of human life, or economic, social or environmental consequences very great'

PD6698 identifies major hazard sites and major accident hazard pipelines as categories of structure that should be designed to withstand low probability events, including earthquakes.



Dams assessed on capacity, height, persons downstream, damage potential score between 0 & 36

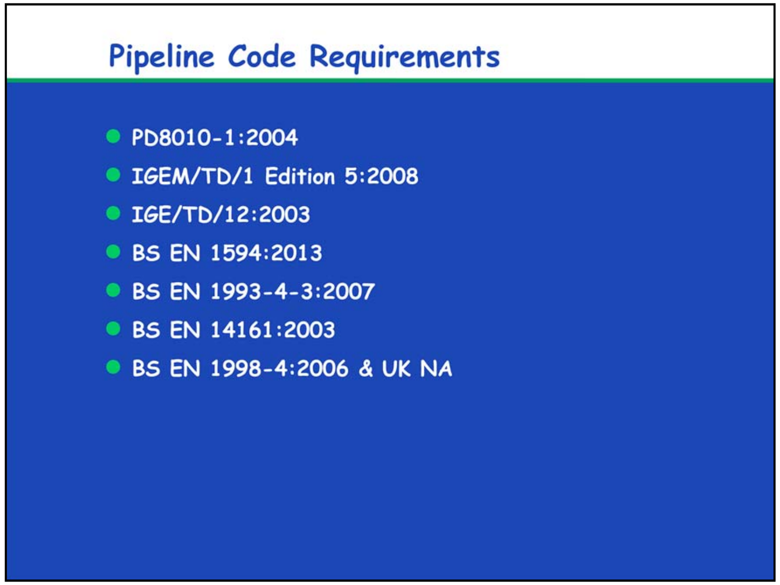
RP 30000 years for Category IV dams (>100 persons & score >30) BUT Large capacity, high dam with >1000 downstream could be CAT III if damage potential none or low.

RP 10000 years for Category III dams (score 19-30)

RP 3000 years for Category II dams (score 7-18)

RP 1000 years for Category I dams (score 0-6)

Chemical Industries Association



PD8010-1:2004. Code of practice for pipelines – Part 1: Steel pipelines on land. **Identifies earthquakes as a potential environmental loading hazard and lists several aspects that should be taken into account.**

IGEM/TD/1:2008. Steel pipelines and associated installations for high pressure gas transmission. **Indicates a requirement for consideration of seismic loading on pipelines and installations in accordance with BS EN 1998-4. Notes potential use of PD6698 hazard map for initial screening.**

IGE/TD/12:2003. Pipework stress analysis for gas industry plant. **Identifies earthquakes as an occasional load which in combination with normal sustained loading can provide an abnormal load case. Permitted VM ~12% higher for abnormal relative to normal load case.**

BS EN 1594:2013. Gas infrastructure – Pipelines for maximum operating pressure over 16 bar – Functional Requirements. **Consideration of seismic action dependent on seismicity of area of pipeline route. Informative annex provided. Importance of dynamic amplification emphasised for above ground installations.**

BS EN 1993-4-3:2007. Eurocode 3. Design of steel structures. Pipelines. **Earthquake loads should be considered where appropriate and make reference to Eurocode 8.**

BS EN 14161:2003. Petroleum and natural gas industries – Pipeline transportation systems. Based on ISO 13623. **Classifies earthquakes as an environmental load and indicates the effects to be considered in the pipeline design.**

BS EN 1998-4:2006. Silos, tanks and pipelines.

Return Periods for Seismic Actions

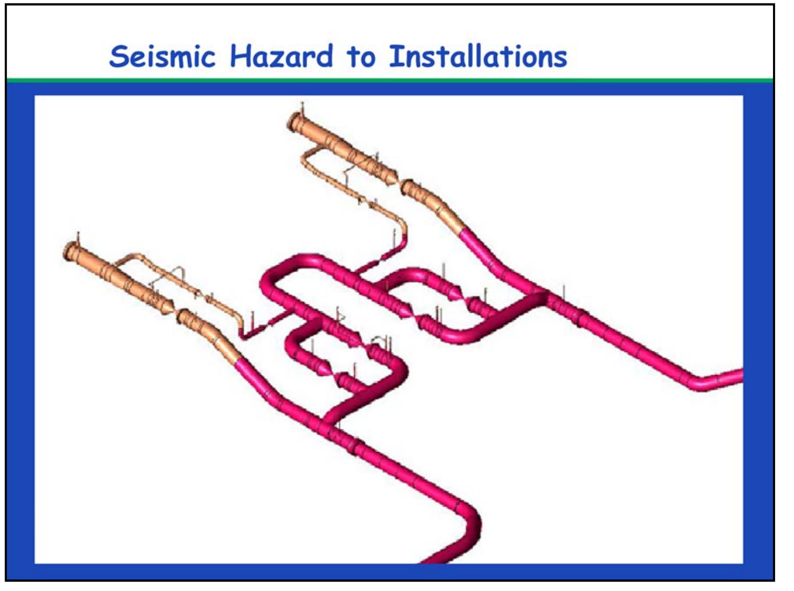
Facility/Structure	Return Period (years)
Eurocode 8: IC III CC3 buildings e.g. schools, assembly halls, cultural institutions etc. & IC III CC3 silos, tanks & pipelines. [high risk to life]	~800
Eurocode 8: IC IV CC3 buildings e.g. hospitals, fire stations, power plants etc.	~1300
Eurocode 8: IC IV CC3 silos, tanks & pipelines. [exceptional risk to life]	~2000
PD 6698: CC3 structures.	2500
BS EN 1473: LNG facilities.	5000
Category III dams, Buildings on chemical manufacturing sites, Nuclear power stations.	10,000
Category IV dams.	30,000

BS EN 1998-4:2006 assigns importance classes I, II, III & IV to structures. The importance class dictates the importance factor which controls the return period for seismic actions. Class I = CC1, Class II = CC2, & Class III/IV = CC3.Class

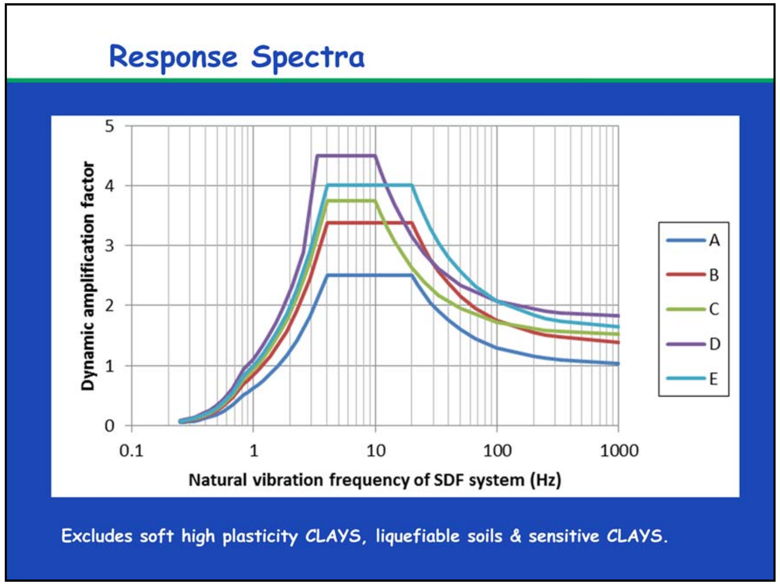
Seismic Hazard to Pipelines

- Strain due to seismic wave propagation
- Permanent ground movement
  - Surface fault rupture
  - Slope instability
  - Liquefaction

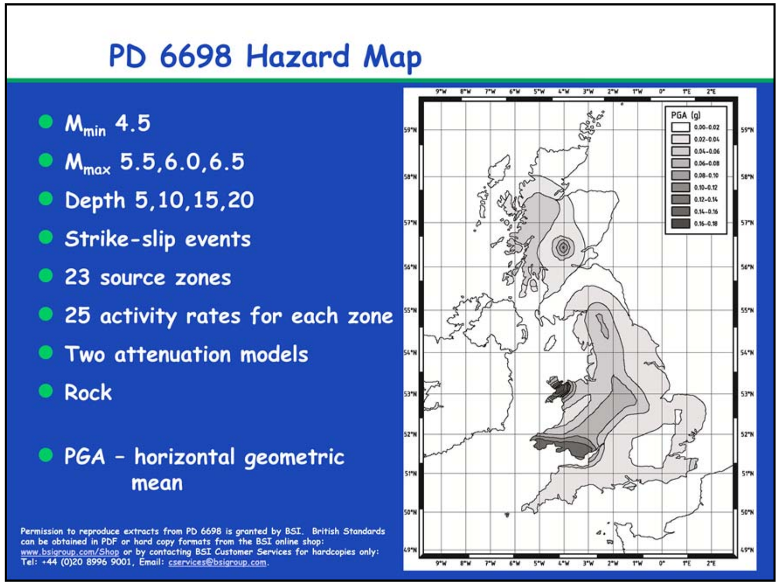
- Seismic Hazard
  - PGA
  - PGV
  - MMI or EMS Intensity



First mode 1 Hz horizontal mode transverse to piping.

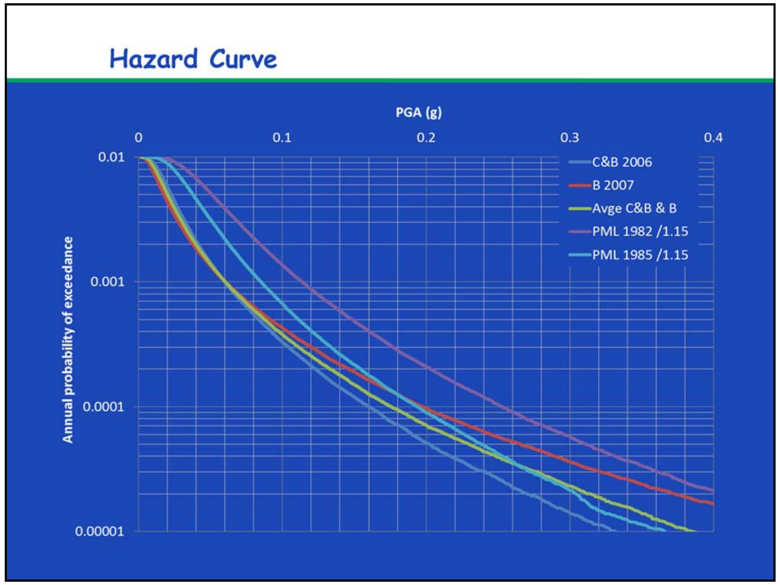


Type 2 elastic response spectra (5% damping) according to EN 1998-1:2004.



$4x10^{-4}$ annual probability of exceedance

PGA up to 0.12g in South Wales, up to 0.18g in north-west Wales


Hazard Curve
PGA (g)
0
0.1
0.2
0.3
0.4
0.01
0.001
0.0001
0.00001
Annual probability of exceedance
C&B 2006
B 2007
Avge C&B & B
PML 1982 /1.15
PML 1985 /1.15

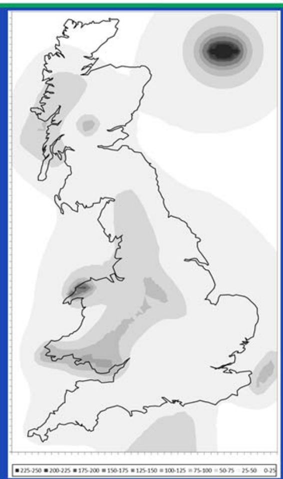
Vulnerability

Ground Shaking											
Fault Rupture											
Liquefaction											
Landsliding											
MMI scale	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
~PGV (mm/s)	< 1	1-10		10-30	30-80	80-160	160-300	300-600	600-1200	> 1200	
~PGA (g)	<0.002	0.002-0.014		0.014-0.04	0.04-0.09	0.09-0.18	0.18-0.34	0.34-0.65	0.65-1.24	>1.24	

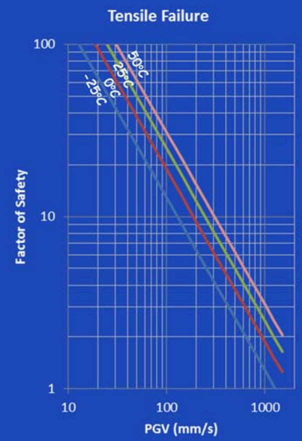
	No damage to steel pipelines
	Damage to steel pipelines with poor quality welds. No damage to pipelines with good quality welds.
	Damage to steel pipelines with modern full penetration butt welds.

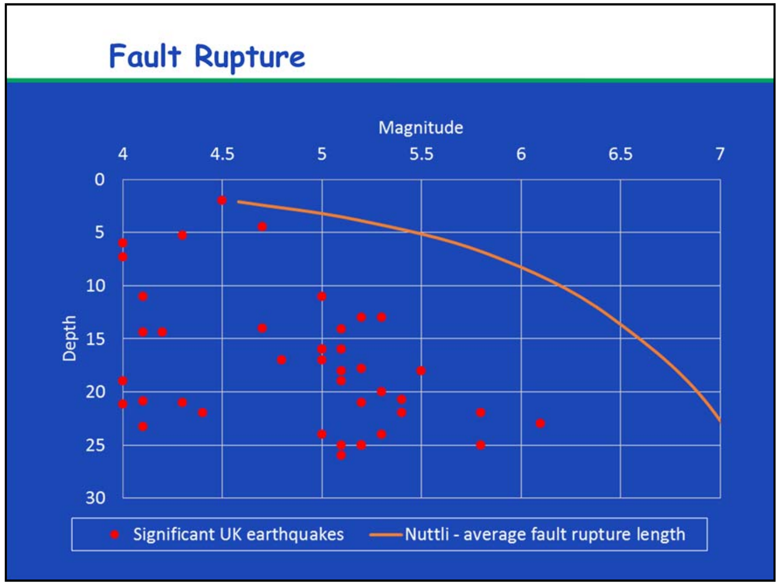
- **17 earthquakes**
- **M_w 5.6-9.2**
- **I_{max} VI-XII**
- **> 180 failures at welds**

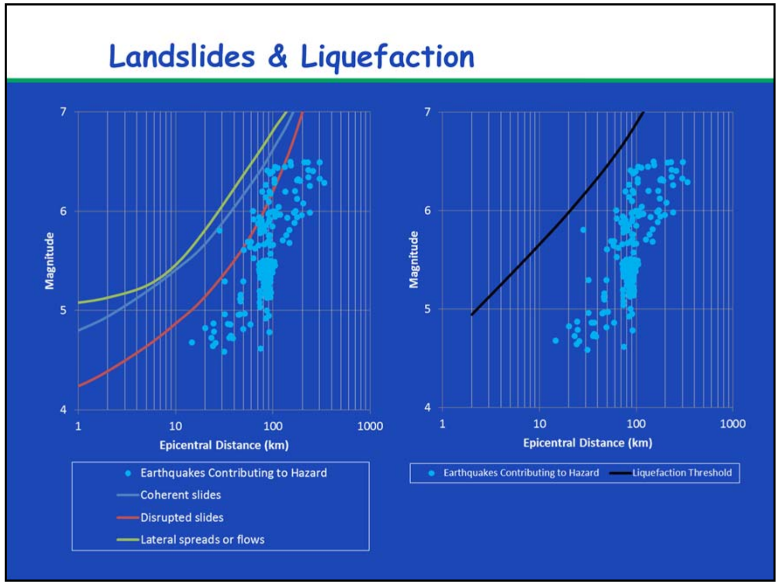
Ground Shaking



PGV (mm/s) 4×10^{-4} APE

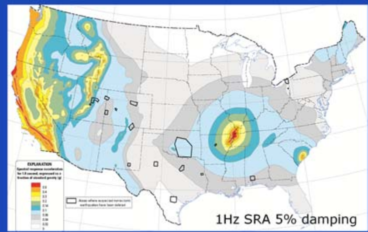



Fault Rupture
Magnitude
4
4.5
5
5.5
6
6.5
7
0
5
10
15
20
25
30
Depth
Significant UK earthquakes
Nuttli - average fault rupture length


Landslides & Liquefaction
Magnitude
Epicentral Distance (km)
Earthquakes Contributing to Hazard
Coherent slides
Disrupted slides
Lateral spreads or flows
Liquefaction Threshold

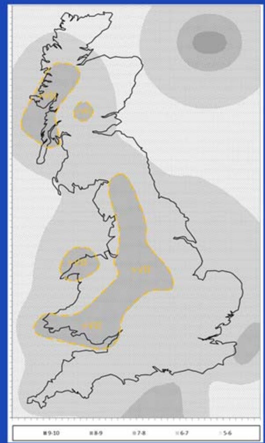
Screening Criteria

- ASME B31.8S 'Managing System Integrity for Gas Pipelines'
  - Fault crossings
  - Liquefiable soils
  - PGA > 0.20g
- ASCE Natural Gas Distribution Systems
  - 1Hz spectral response acceleration > 0.15g for 4×10^{-4} APE

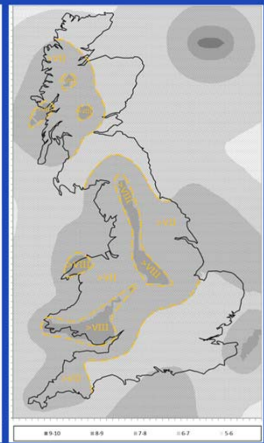


Credit: U.S. Geological Survey

Screening Criteria - Intensity



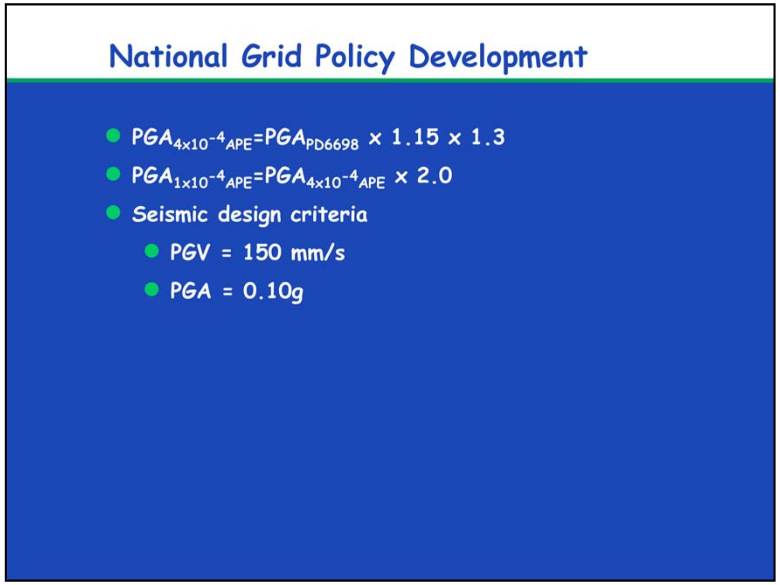
4×10^{-4} APE



1×10^{-4} APE

National Grid Policy Development

- Pipelines & installations (piping)
- Building structures
- Mechanical plant
- Electrical equipment



Hazard model gives PGA ratio 10000yrs/2500yrs of 1.4-2.9 average 1.8

National Grid Policy Development

Importance Class	Area Type [Safety]			
Outage	Remote	Rural [≤10 potential casualties]	Suburban [≤100 potential casualties]	Town [≤1000 potential casualties]
Short [~1 day]	I or II	II	III	IV
Medium [~1 wk]	II or III	II or III	III	IV
Long [>2 wks]	III or IV	III or IV	III or IV	IV

Importance Class	I	II	III	IV
Importance Factor γ_I	n/a	0.45	1.0	2.0

SSSHA if potential for >1000 casualties

$$\boldsymbol{PGA_{soil}} = a_g.\boldsymbol{S} = \gamma_f.\gamma_I.a_{gR}.\boldsymbol{S}$$

γ_f=1.5, $\boldsymbol{S}$ =1.35-1.8

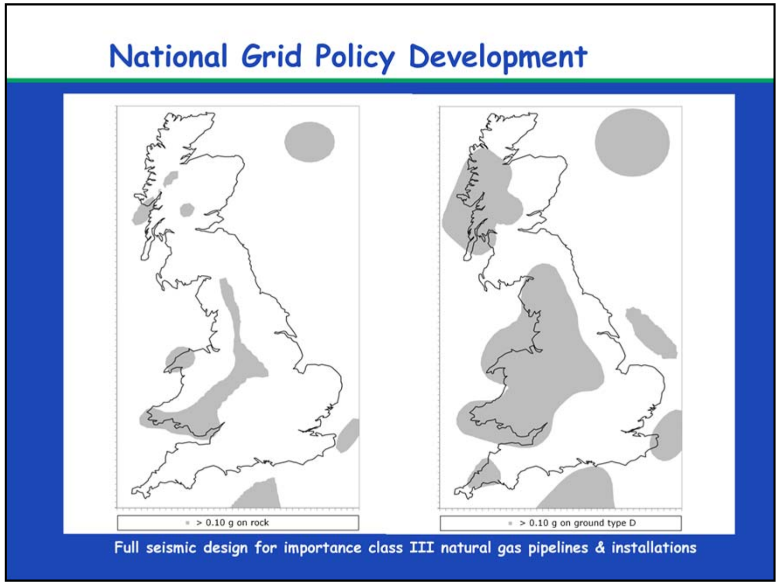
Hazard model gives PGA ratio 10000yrs/2500yrs of 1.4-2.9 average 1.8

Hazard model gives S=1.1-1.15

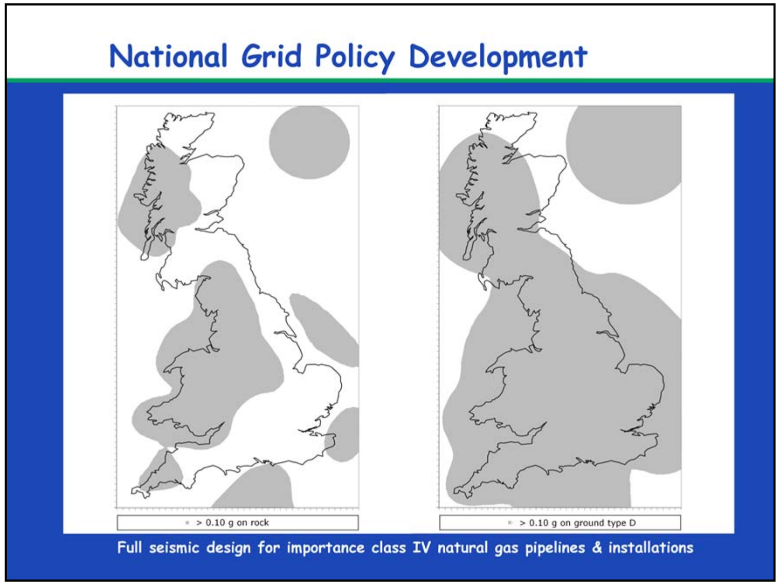
National Grid Policy Development

Screening & Design

IC & $a_g.S$	Pipelines	Installations
IC=I & IC=II ($a_g.S \leq 0.1g$)	None	None
IC=II ($a_g.S > 0.1g$) IC=III or IV ($a_g.S \leq 0.1g$)	None	Simplified
IC=III or IV ($a_g.S > 0.1g$)	PGV & PGM	Detailed
IC>IV (SSSHA)	PGV & PGM	Detailed



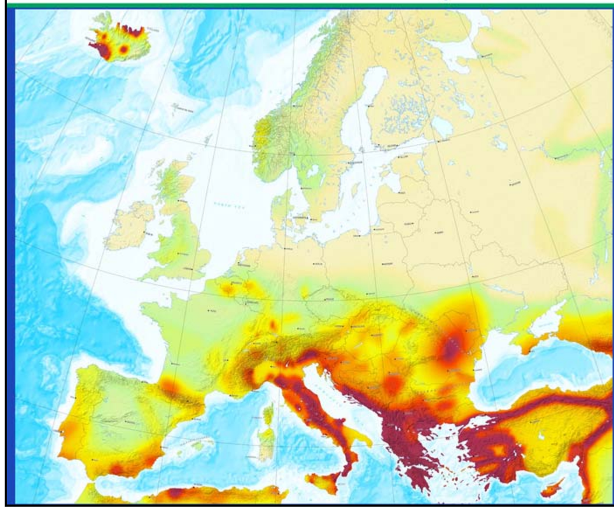
Full seismic design:


National Grid Policy Development
> 0.10 g on rock
> 0.10 g on ground type D
Full seismic design for importance class IV natural gas pipelines & installations

Recommendations

- UKOPA Guide to Seismic Risk in the UK
  - Hazard Differentiation?
  - Return Period Differentiation?
  - Return Periods
  - Criteria & Levels of Assessment
- Hazard Map(s)
- Clarify practice in continental Europe
- Clarify U.S. screening criteria

Seismic Hazard - Europe



10% chance of exceedance in 50 years

Credit: European Seismological Commission

UNESCO-IUGS International Geological Correlation Program Project no. 382 SESAME 2003