Seismic (Strain-Based) design for high pressure pipeline in Japan

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Contents

- Linepipe products development flow
- Hostile environment for pipeline
  - Global networks and Earthquakes
- Seismic design for pipeline
  - Example of damages in earthquake
  - Design codes
- Study on bending capacity in JFE
  - Full scale test example
  - High-strain pipe’s bending capacity
Material Development Flow

**Micro Structure Control**

- Structural Analysis
  - Structure performance
- Mechanical properties

**Process development & control**

- Nano-microstructure
- Micro Mechanics

**Material Performance**

- Conventional (Q-T)
- New Process (Bainite + MA)

**Graph**

- Stress (MPa)
- Strain (%)

**Images**

- Accelerated cooling
- Rapid heating
- Super-OLAC®-A
- HOP®

- Bainite-MA
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Major gas trade movements 2013

※ Source: BP Statistical review of world energy 2014
Earthquake areas in the world

Preliminary Determination of Epicenters
358,214 Events, 1963 - 1998

Image is Public domain
## Risks effect on pipelines

<table>
<thead>
<tr>
<th>Risks</th>
<th>Onshore</th>
<th>Offshore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic region</td>
<td>![Circle]</td>
<td>![Circle]</td>
</tr>
<tr>
<td>- Shake, spreading, fault</td>
<td>![Circle]</td>
<td>![Circle]</td>
</tr>
<tr>
<td>Steep slope stability</td>
<td>![Circle]</td>
<td>![Circle]</td>
</tr>
<tr>
<td>Densely populated</td>
<td>![Circle]</td>
<td>![X]</td>
</tr>
<tr>
<td>Cold region</td>
<td>![Permafrost]</td>
<td>![Ice gouge]</td>
</tr>
<tr>
<td>Deep water (External Pressure)</td>
<td>![X]</td>
<td>![Circle]</td>
</tr>
<tr>
<td>Strong current</td>
<td>![X]</td>
<td>![Circle]</td>
</tr>
<tr>
<td>Bottom irregularity</td>
<td>![X]</td>
<td>![Circle]</td>
</tr>
<tr>
<td>Strain during construction</td>
<td>![X]</td>
<td>![Circle]</td>
</tr>
</tbody>
</table>
Gas pipeline in Japan capital

※ Source: Tokyo-gas

Natural gas pipeline network of Tokyo-gas

※ Source: Chiba prefecture

Seismic intensity
6 (JP)

Liquefaction risk map by Chiba pref.

High pressurized gas pipeline (TokyoGAS)
Gas pipeline (Other company)
Gas supply area (Direct by TokyoGAS)
Gas supply area (via Other Company)
Permanent Ground Deformation

Lateral spreading near slope

Lateral spreading near embankment
※ Source: shear.nagaokaut.ac.jp Dr. Toyota

Land slide in hill-side, pipe in the air
※ Source: Tokyo-gas

Land slide
※ Source: Niigata Nippo
Pipeline damage: 921 Eq. (1999)

Area: Taiwan
Magnitude: 7.6-7.7Mw

Underground pipeline for waterworks
2 meters of Diameter and 18mm in Wall thickness

※ Source: Farshad Vazinram “Seismic Hazards for Lifelines” 2006
※ Source: Weihao.chiu
Pipeline damage: İzmit Eq. (1999)

Area: Turkey
Magnitude: 7.4-7.5 Mw

Damage to a water trunk line observed.

※ Source: Farshad Vazinram “Seismic Hazards for Lifelines” 2006
※ Source: JFE Engineering
Contents

• Linepipe products development flow
• Hostile environment for pipeline  
  – Global pipeline networks and Risks
• Seismic design for pipeline  
  – Example of damages in earthquake  
  – Design codes
• Study on bending capacity in JFE  
  – Full scale test example  
  – High-strain pipe’s bending capacity
Ordinal pipeline design (Stress-based)

(a) Internal pressure
\[ \sigma_p = \frac{P \times d_{in}}{2 \times t} \]
- \( \sigma_p \): Stress caused by pressure
- \( P \): Internal pressure
- \( d_{in} \): Inside diameter
- \( t \): Wall thickness

(b) Soil pressure
(c) Live load by vehicles (if buried under road)
(d) Change in temperature
(e) Stress caused by ordinal earthquakes

Sum of each stress must be less than allowable stress. 
Diameter and wall thickness is set to meet the design.
Strong Earthquakes in Japan

1983 Nihonkai-Chubu eq.
- Subduction zone earthquake (M7.7)
  → Tsunami
  → Liquefaction
  → Long-period ground motion

1964 Niigata eq.
- Subduction zone earthquake (M7.5)
  → Tsunami
  → Liquefaction

2011 Tohoku eq.
- Subduction zone earthquake (M9.0)
  → Tsunami
  → Liquefaction
  → Long-period ground motion

1995 Kobe eq.
- Strong local earthquake (M6.8)
  → Strong motion to structure
  → Liquefaction
  → Land slide
  → Fault movement

Source: http://www.hinet.bosai.go.jp/about_earthquake/PNG/fig6.7.png
Past Studies on PGD by Liquefaction

Kobe Earthquake (1995)
Magnitude : 6.8 MW

Source : Hamada (Waseda Univ. 2004)

Volumes of lateral spread at surface [cm]

Direction

Confidential
Break incident induced by PGD

Nihonkai-Chubu Earthquake (1983)
Magnitude : 7.7 M

Gas pipeline break in its bend (1983 Nihonkai-chubu eq.)

Source : Hamada (Waseda Univ. 2004)
## Seismic Design Codes in Japan

<table>
<thead>
<tr>
<th>Earthquakes in Japan</th>
<th>Year</th>
<th>Design Codes</th>
<th>Check Items</th>
<th>Critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964 Niigata</td>
<td>1974</td>
<td>Petroleum Pipeline Design Code</td>
<td>Ground motion</td>
<td>Allowable stress</td>
</tr>
<tr>
<td>1968 Tokachi-oki</td>
<td>1982</td>
<td>Seismic Design Code for Pressurized Gas Pipelines</td>
<td>Ground motion</td>
<td></td>
</tr>
<tr>
<td>1983 Nihonkai-Chubu</td>
<td>2000</td>
<td>Seismic Design Codes for HP Gas Pipelines (1st)</td>
<td>Ground motion (Level -2)</td>
<td>Allowable strain</td>
</tr>
<tr>
<td>1993 Kushiro-oki</td>
<td>2001</td>
<td><strong>Seismic Design Codes Considering Liquefaction for HP Gas Pipelines</strong></td>
<td>Lateral spreading</td>
<td>Allowable bending angle, strain</td>
</tr>
<tr>
<td><strong>1995 Hyogoken – nanbu (Kobe)</strong></td>
<td>2004</td>
<td><strong>Seismic Design Codes for HP Gas Pipelines (2nd)</strong></td>
<td>Ground motion (Level -1,2)</td>
<td>Allowable strain</td>
</tr>
</tbody>
</table>
### TGD and PGD: Strain Based Design

Allowable strain and allowable deformation of high-pressure gas pipelines

<table>
<thead>
<tr>
<th>Ground Displacement</th>
<th>Deformation Mode</th>
<th>Limit State</th>
<th>Allowable Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporary Ground Deformation</td>
<td>Ground motion Level-1</td>
<td>Cyclic axial deformation (N=50)</td>
<td>Normal Operability</td>
</tr>
<tr>
<td></td>
<td>Ground motion Level-2</td>
<td>Cyclic axial deformation (N=3-5)</td>
<td>Pressure integrity</td>
</tr>
<tr>
<td></td>
<td>Lateral spreading etc..</td>
<td>Bending deformation (Irreversible: one-side bending)</td>
<td>Pressure integrity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bend: opening 10% closing 30%</td>
</tr>
</tbody>
</table>

- **Temporary Ground Deformation**: Ground motion Level-1 and Level-2
- **Permanent Ground Deformation**: Lateral spreading etc..

![Diagram showing Ground Displacement and Pipeline Deformation](image)
“Seismic Design Codes for HP Gas Pipelines”

**Application to:**
For steel pipe connected longitudinally by Girth weld.

**Material:**
- API 5L X42 – X65, STPG (JIS) 370, 410, STPT (JIS) 370, 410, 480, STPY 400
- Specified Minimum Yield Stress (SMYS) range 215 – 531 MPa

**Weld Design:**
- Penetration is enough, w/o harmful flaw, enough strength needed by design.
Design flow for Ground Motion (TGD)

1. Route surveying Pipe geometry
2. Search active-fault near pipeline location
3. Active fault move or not?
   - YES: Seismic motion calculation
     - Strong-local eq.
     - Subduction-zone eq.
     - Calculate soil strain and transmitted strain to pipeline
     - Strain demand lower than strain capacity
       - YES: OK
       - NO: Change route, Change pipe geometry

   - NO: Strain capacity in seismic code
     - Level 1: 1%
     - Level 2: 3%
Temporary ground motion Lv1-2 (TGD)

Propagation of surface wave

Maximum ground strain by surface wave

Ground strain at pipeline buried: \( \varepsilon_{\text{Gpl}} = v \cdot \varepsilon_G \cdot \cos(\pi z / 2H) \)

Pipe strain: \( \varepsilon_p = \varepsilon_{\text{Gpl}} \cdot \alpha \)

(Strain transfer coefficient: \( \alpha \) is defined by wave length, pipe and soil spring stiffness)
“Seismic Design Codes Considering Liquefaction for HP Gas Pipelines”

Application to:
For steel pipe connected longitudinally by Girth weld.
Material Inspection, Welding procedure and Welded part Inspection, and pressure and leak test is needed.

Material:
API 5L X42 – X65, STPG(JIS) 370, 410, STPT (JIS) 370, 410, 480, STPY 400
Specified Minimum Yield Stress (SMYS) range 215 – 531 MPa

Weld Design:
Penetration is enough, w/o harmful flaw, enough strength needed by design.
Design Codes for Liquefaction

Route surveying
Pipe geometry

Surveying liquefaction area near PL Location

In liquefaction area?

YES → Calculate Ground deformation

Calculate Pipe deformation

Strain demand lower than strain capacity

YES → OK

NO → Route change, Change pipe geometry

Strain capacity in seismic code

Straight pipe: 30%
Bend pipe: 10% for opening, 30% for closing

※ FEA or Exp. allowed to investigate strain capacity of actual pipe.
Two types of PGD during liquefaction

**Surface displacement**
- No liquefied layer
- Liquefied layer

**Inclines**
- Move dir.
- PGD

**Backfills**
- Ocean
- Liquefied layer

**Type-a**:
- Lateral spreading by the inclined liquefied ground layer

\[ \delta_h = 36 \cdot c \cdot f_{soil} \cdot \theta_g \]
- \( c \) : half for civilized area
- \( f_{soil} \) : calculated by soil information
- \( \theta_g \) : ground inclination

**Type-b**:
- Lateral spreading by the revetment moves toward the ocean

\[ \delta_h = \Delta_w \cdot \exp(-3.35 \cdot \frac{L_{wp}}{L_{w0}}) \]
- \( \Delta_w \) : Revetment move distance
- \( L_{wp} \) : pipe-revetment distance
- \( L_{w0} \) : liquefied area

Two major types of PGD induced by liquefaction
Strain capacity of Higher grade linepipes

- Higher grade is widely used
  - More gas with higher pressure
  - High grade pipe like X80 (555MPa), X100 (700MPa) have been applied

- For higher grade (higher YS) of linepipes?
  - Both codes apply for upto YS=531 MPa material.
  - Strain capacities written are those for ordinal pipes.
  - Higher grade pipe tend to have higher Y/T …

Seismic codes allow to use detailed study using
  (1) Experiment with actual pipe.
  (2) FEA based investigation.
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JFE test rig series for structural test.

Axial Compression Test

OD ~36” pipe

Bending test

For OD 48” pipe
Pipe deformation in bending test

Elastic deformation

Critical deformation
Buckling wrinkle

Post-buckling deformation
Wrinkle development
↓
bending concentration

Limit-state deformation
Tensile strain concentration
↓
Break in tension

Normal operability

Pressure integrity

Peak moment
Material Development Flow

- **Structural Analysis**
- **Structure performance**
- **Micro Mechanics**
- **Mechanical properties**
- **Nano-microstructure**

**Micro Structure Control**
- **Process development & control**

**Graphical Content**
- Stress vs. Strain graph
- Comparison between Conventional (Q-T) and New Process (Bainite + MA)
- Rapid heating
- Accelerated cooling
- Super-OLAC®-A
- HOP®
X80 48” pipe bending tests (comparable)

- X80 linepipe: 48” (1219mm) OD X 22mm WT (D/t 55.4)
- Internal Pressure: 12MPa (60% SMYS of X80)
- Tensile properties of tested materials

<table>
<thead>
<tr>
<th>Pipe type</th>
<th>YS [MPa]</th>
<th>TS [MPa]</th>
<th>Y/T [%]</th>
<th>uEL [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hi-strain “HIPER®”</td>
<td>585</td>
<td>701</td>
<td>84</td>
<td>8.0</td>
</tr>
<tr>
<td>Conventional</td>
<td>596</td>
<td>658</td>
<td>91</td>
<td>6.4</td>
</tr>
</tbody>
</table>
Pipeline Bending Test Rig for 48” OD pipe

Capacity of the pipe bending test apparatus
- Pipe diameter : 48”
- Pipe length : 8 m
- Load capacity : 6,000 kN
- Moment capacity : 35,000 kNm
Test result of high-strain pipe HIPER®

Largest buckling wave at center ~1.2m

Moment - rotation

Buckling

(14.1 deg., 17.9 MNm)

M [MN-m]

θe [deg.]

0 5 10 15 20 25

0 5 10 15 20 25
Test Result for Conventional Pipe

- Largest buckling wave at center +2.75m
- Break at backside of buckling wave.

Moment - rotation

- Buckling: (8.2°, 17.3 MNm)
- Break: (19.8°, 12.3 MNm)
Bending Capacity: X80 HIPER® vs. Conv.

Bending angle – Moment relationships

![Diagram showing bending angle vs. moment relationship for X80 HIPER® and conventional pipes.]

Test Results Summary

<table>
<thead>
<tr>
<th>Type</th>
<th>Buckling</th>
<th>Ultimate State</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M [MN-m]</td>
<td>Angle [deg.]</td>
</tr>
<tr>
<td>HIPER®</td>
<td>17.9</td>
<td>14.1</td>
</tr>
<tr>
<td>Conv.</td>
<td>17.3</td>
<td>8.2</td>
</tr>
</tbody>
</table>

↓: Max moment
*: Break

Normal operability
Conclusion

• Seismic Design for High pressurized gas pipeline
  – Study from actual damage case in Japan.
    • Ex. 1995 Kobe Earthquake, 1964 Niigata Eq. and so on.
  – Temporary Ground Deformation (TGD) ← Smaller
    • Induced by Ground Motion during earthquake.
  – Permanent Ground Deformation (PGD) ← Larger
    • Induced by Liquefaction during and after earthquake.

• Strain Capacity for Linepipe in SBD project.
  – Uniform deformation until buckling : for Normal Operability
  – Deformation until rupture : for Pressure Integrity
  – JFE developed high strain pipe “HIPER®” which have high strain capacity by stress-strain curve control.
Dinlediğiniz için teşekkür ederim

More information?
  a) Seismic design for gas pipelines in Japan
     Please search “Japan seismic design gas pipeline”
  b) 48-inched pipe bending test rig
     Please search “JFE 48inch”