MANAGEMENT OF HYDROTECHNICAL THREATS TO TRANSPORT PIPELINES AT RIVER CROSSINGS: ADVANCES AND CHALLENGES

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Hydrotechnical Hazards

- **Advances**
  - **Development of river crossings program**
  - **Comprehensive Integrity Study**
  - **Pipeline susceptibility**
  - **Risk Analysis**

- **Challenges**
  - **Development of early warning systems**
  - **Response to emergency**
  - **Calibration of stress analysis calculations under a free-span condition**

Hydrotechnical Hazards

1. Flooding
2. Vertical scour (or accretion)
3. Lateral scour (or accretion) due to curves and meanders
4. Avulsion (particularly along the Right-of-way)
5. Buoyancy
6. Impacts from Debris flow
7. Rapid lake drainage (outburst flooding)
8. Coastal inundation (tsunami)
9. Combination of more than one of the above!

Hydrotechnical Hazards

Vertical Scour

Lateral Scour

Flooding +Avulsion ROW +buoyancy

Impact from Debris flow

Elements of a River Crossings Program

1. ***Monitoring program***
2. **Screening to define priorities**
3. ***Comprehensive Integrity studies***
4. **Risk Analysis**
5. **Risk management**
6. **Implementation of remediation works**
7. **Early warning system**
8. **Response to emergency**
9. **Development of a data base and its integration to a GIS**
10. **Financial planning**
11. **Insurance policies comprising river crossings and its remediation works**

1. and 3. Main sources of data needed to risk analysis

Comprehensive Integrity Study for River Crossings

- **IPG Commitment to Hydrotechnical Hazards:**

IPG 2013 Tutorial, Bogotá, Colombia July 24 – 26. 2013

Studies for the design of crossings of water bodies

Prof. Manuel García López, José Vicente Amórtegui

- **Elements of an Integrity Study**

1. **Geo-referenced depth of cover measurements along each pipeline**
2. **Soil sampling and laboratory analysis**
3. **Topography/Digital Terrain model at river reach around the crossing**
4. **Hydrological modeling**
5. **Hydraulic modeling**
6. **Scour calculations**
7. **Lateral migration by means of chronological analysis of images (satellite/flights/drones)**
8. **Conclusions**

Later on, an example is shown to visualize each ser of data

Risk Analysis – Risk of what?

Lost of containment of transported fluid

(includes pipeline vulnerability and stress analysis)

- **Very common: risk of exposure (water resources agencies)**
- **Usually biased since it is based only on considering vertical scour.**
- **It does not consider pipeline resistance**
- **Big difference among the two in terms of budget necessary to comply**

Risk Analysis – How to select a method?

- **Must be able to include all the natural processes associates to river crossings**
  - **Scour, lateral migration, avulsion, encroachment, etc.**

- **Needed input data must be easy to obtain**

- **Monitoring activities should be defined with the chosen risk analysis method in mind**

Risk Analysis – Most common methods

- **Qualitative (colored matrix)**
- **Semi-quantitative (Index based)**
- **Quantitative (probability based):**
  - **Has de advantage of allowing to compare to other probabilities of failure coming from other threats (corrosion, third party, operational, etc.)**

Risk Analysis dilemma

- Subjective vs Objective in selection of probabilities
- Efforts should be made to include as much engineering in the selection process (objective part)
- Still, expert judgement plays an important role (subjective part)

Quantitative Risk Analysis and Pipeline Susceptibility
Main Equation: Probability of Failure
After Rizkalla/Read: Pipeline Geohazards Planning, Design, Construction and Operations, ASME

$$S_{Gi} = I_i . F_i . V_i . M_i$$

- S_{Gi} : Susceptibility (or annual PoF) due to occurrence of the geohazard;
- I_i Initiation feasibility of the geohazard representing the degree of certainty that a geohazard occurrence at a specific location is feasible or infeasible (“gate variability);
- F_i: Frequency of occurrence of the geohazard representing number of events per year at a given location based on an estimated recurrence Interval;
- V_i: Vulnerability of the pipeline to a geohazard occurrence representing the degree of damage expected as a result of exposure of the pipeline to the geohazard, implicitly accounting for spatial and temporal conditional probabilities of pipe-soil interaction;
- M_i: Mitigation factor representing the beneficial effects of mitigation measures installed during construction and, if necessary, during operation of the pipeline to reduce geohazard impact

I_i Initiation – How Certain

Initiation – how certain?

0	Not possible, missing essential condition(s) for occurrence
0.001	Not credible, no evidence of past occurrence, almost certain that permissible conditions for occurrence do not exist
0.01	Uncertain, permissible conditions for occurrence may exist but insufficient information to confirm or refute
0.1	Credible, no evidence of past occurrence, permissible conditions most likely to exist based on proximate locations or stability analysis
1	Certain, permissible conditions exist, evidence of past occurrence or observed instability at site

Easy Pick = 1

F_i Frequency of occurrence – How Often?

Recurrence – how often?

0.0001	One occurrence every 10,000 years
0.001	One occurrence every 1000 years
0.01	One occurrence every 100 years
0.1	One occurrence every 10 years
1	One occurrence every 1 year (use as minimum for active areas) or
1/T	Where T is time to reach a critical state if site conditions are changing (maximum = 1)

Given by:

- **Codes & Regulations, Government agencies**
- **Own policy defined by an Operator**
- **River´s own capacity**
- **Defined by the extent of remediation works: temporary, intermediate, definite**
- **Not a great variability: usually 50 to 100 year of return period**

Pick = 0.01 – 0.02

V_i Vulnerability – How Extensive? How rapid? How Fragile?

Spatial reach – how extensive?

0	Pipeline does not intersect Geohazard Zone of Influence (GZI) or buffer
0.01	Pipeline intersects GZI buffer in zone of accumulation
0.1	Pipeline intersects GZI buffer in zone of depletion or GZI in zone of accumulation
1	Pipeline intersects GZI in zone of depletion

Duration – how rapid?

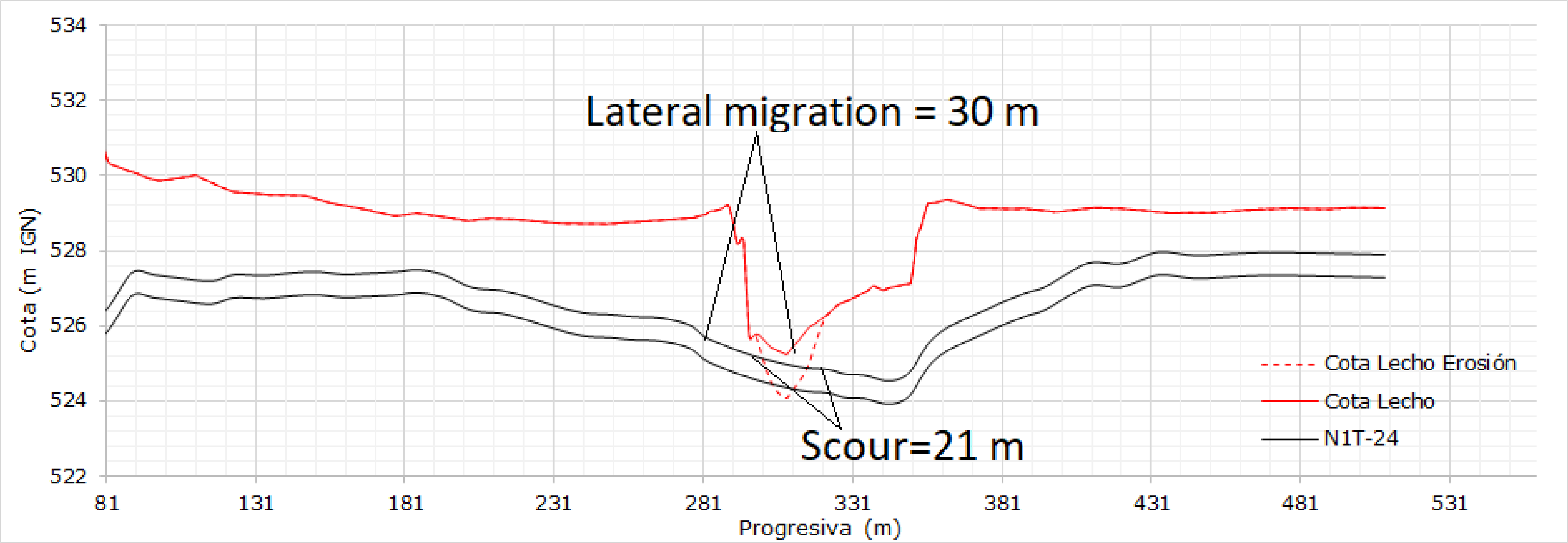
0.1	Geohazard expected to develop gradually; sufficient time to intervene before impact
1	Geohazard expected to develop rapidly; insufficient time to intervene before impact
	or
v/d	Where d is the travel distance to the pipeline and v is velocity of movement (maximum value of 1)

Vulnerability – how fragile?

0	No impact on pipeline
0.001	Impact on pipeline is inconsequential (0.1% chance of realizing risk context), addressed by planned maintenance
0.01	Impact on pipeline is minor disturbance (1% chance of realizing risk context), addressed by planned mitigation
0.1	Impact on pipeline is a non-compliant state (10% chance of realizing risk context), addressed by unplanned mitigation
1	Impact on pipe is loss of containment (100% chance of realizing risk context), addressed by emergency response

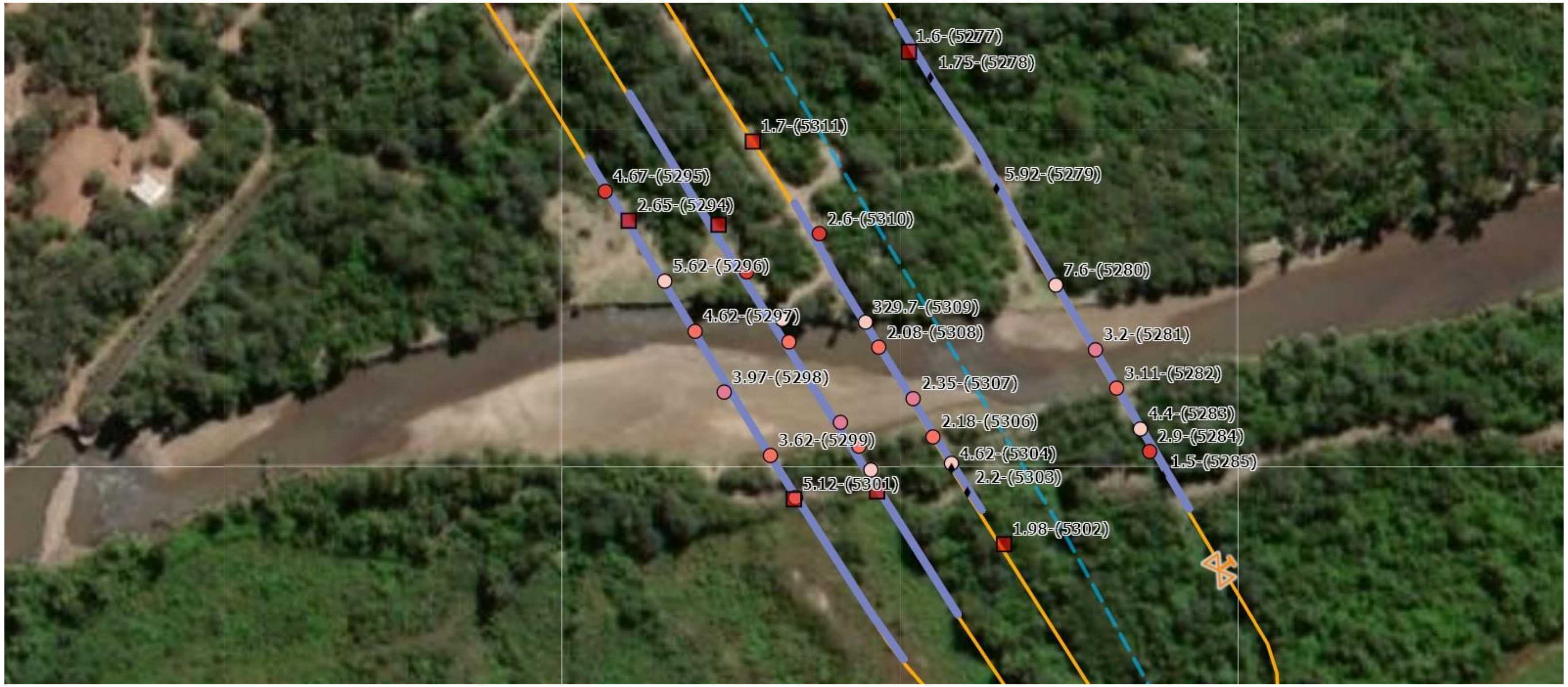
V_i Vulnerability – How Extensive?

- Topography
- Geo-referenced depth of cover measurements
- Scour calculations.: Soil sampling, hydrological modelling (design Flow), hydraulic modelling (water velocity, depth, surface elevation)



V_i Vulnerability – How rapid?

- **Monitoring: successive depth of cover measurements along time (vertical scour)**
- **Chronological study of satellite images, photographs and drone pictures (lateral migration)**



V_i Vulnerability – How fragile?

Forces:

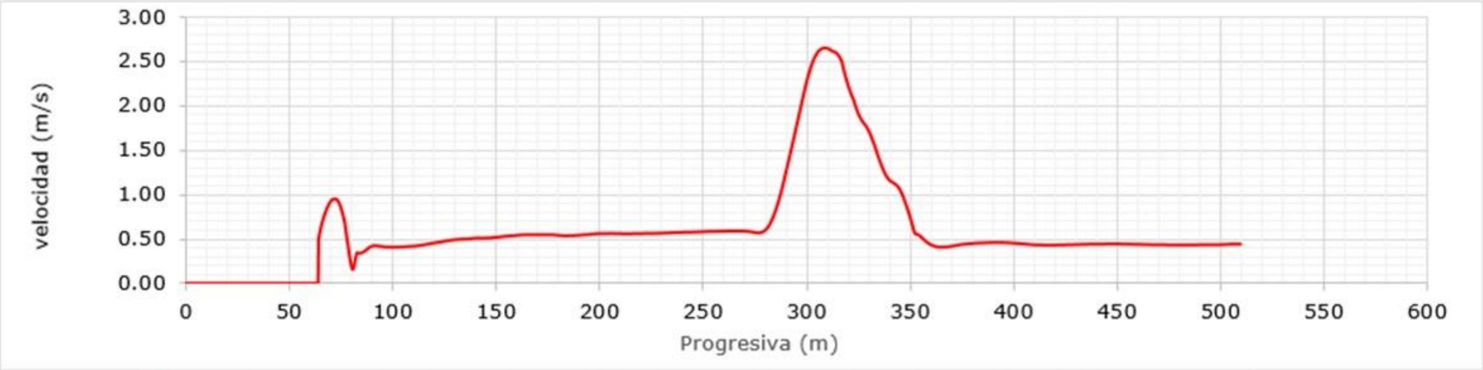
- **Drag**
- **Vortex induced vibration (fatigue)**
- **Buoyancy**
- **Impacts from debris flows**
- **Torsion (particularly when set backs are exposed)**
- **Third-parties impacts (watch out for anchors!!!!)**

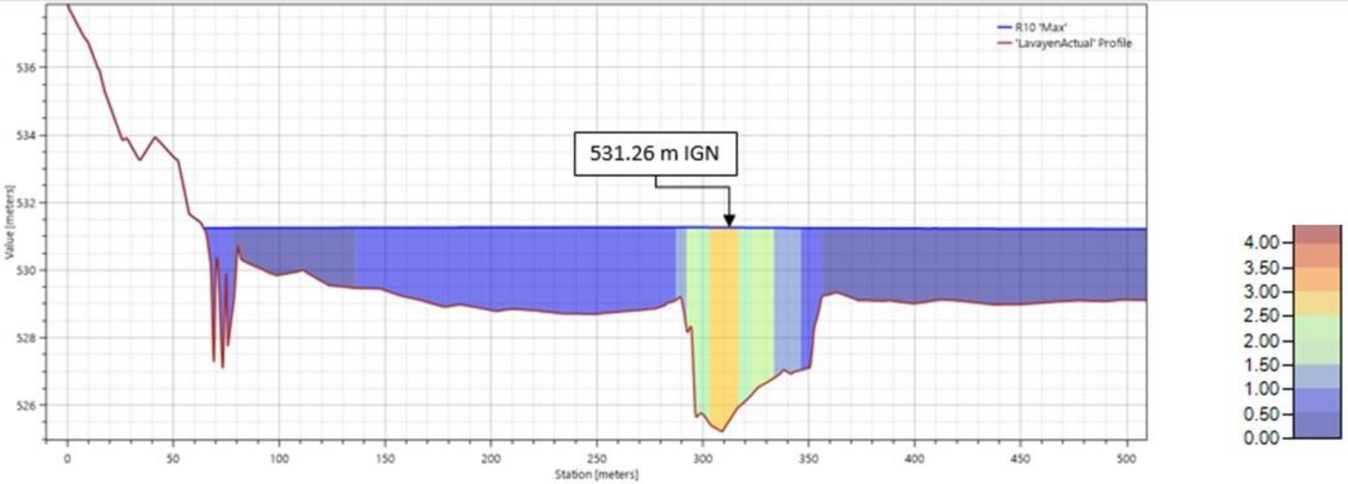
V_i Vulnerability – How fragile?

(Here goes a video of an exposed pipe under Vortex Induced Vibration)

V_i Vulnerability – How fragile?

Velocity profile from hydraulic modelling along crossing: V=2.7 m/seg





V_i Vulnerability – How fragile?

Maximum Allowable Length in free-span in a situation

API 1133 equations or River-X Software or Finite-element Method: Drag: 27 m, VIV: 21 m

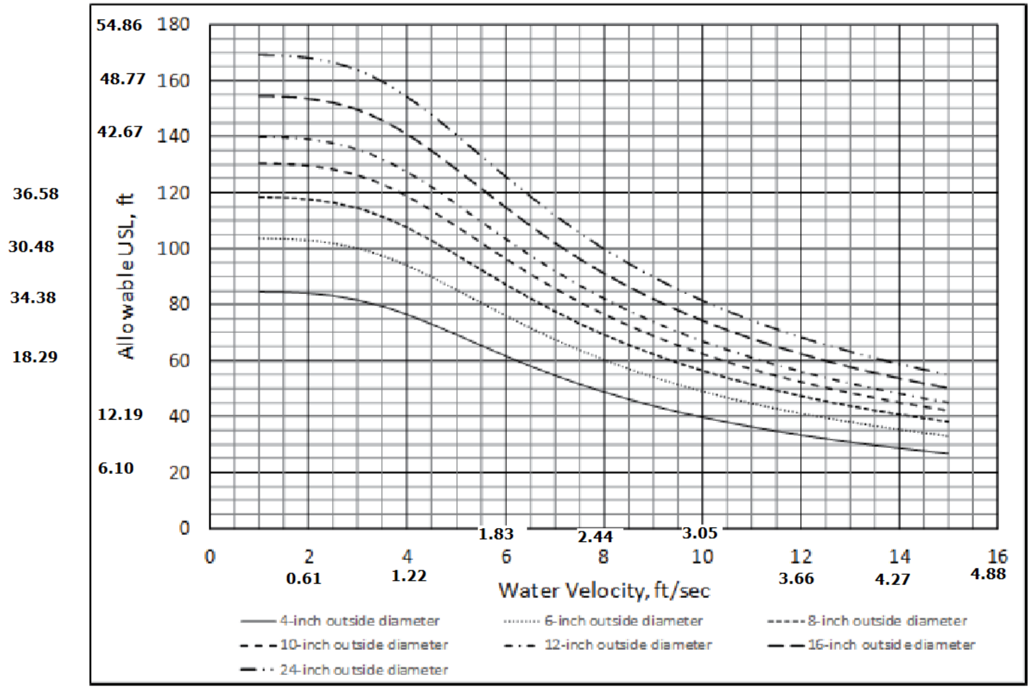


Figure E.1—Example Relationship between Water Velocity and Allowable USL

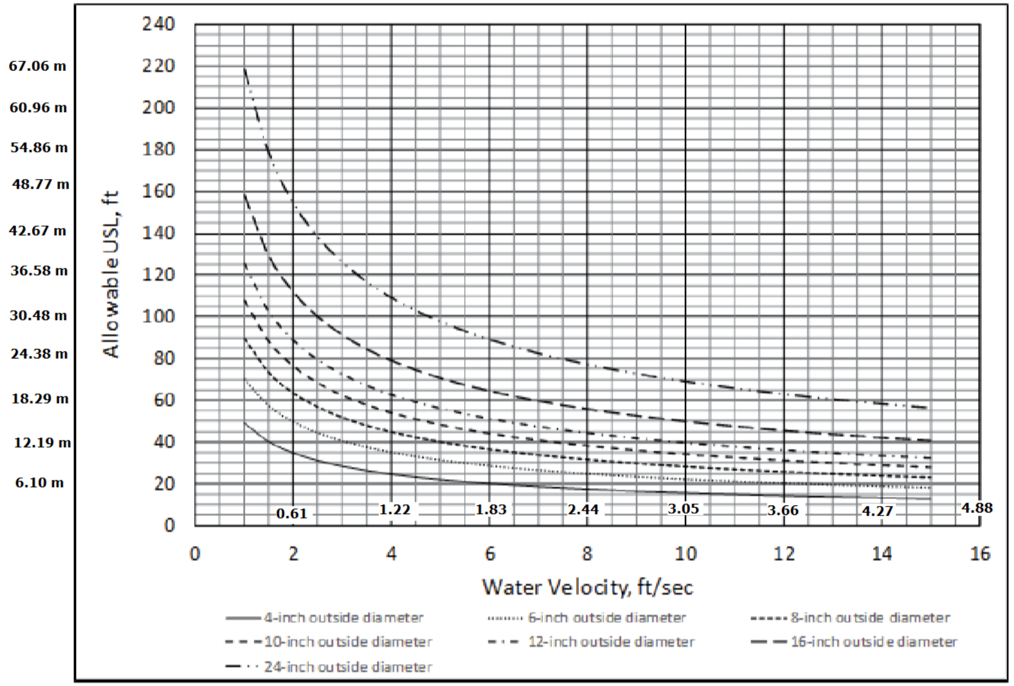


Figure E.2—Example Relationship between Water Velocity and Allowable USL Relative to VIV

V_i Vulnerability – How fragile?

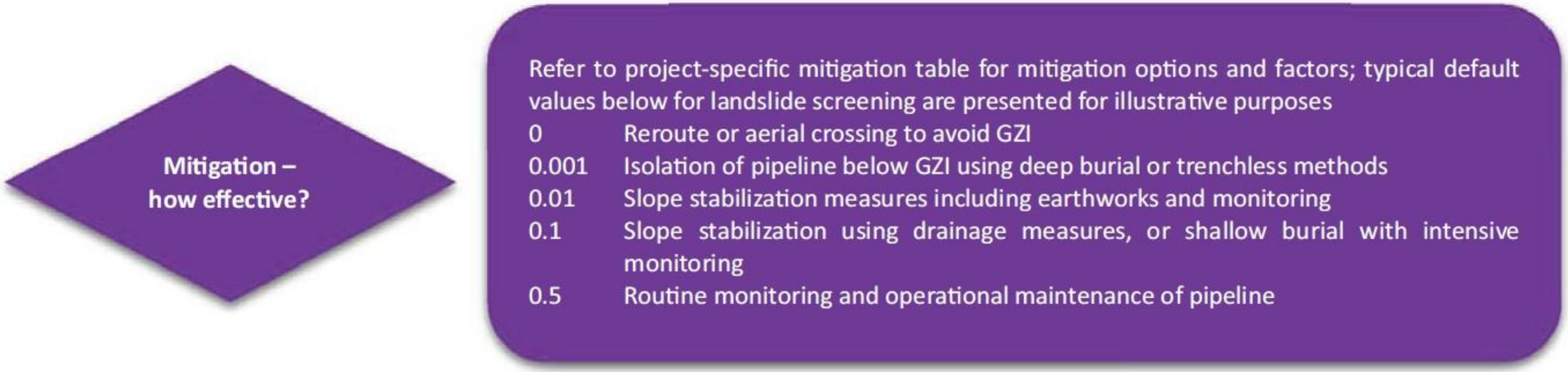
- **Besides calculations, Free-span analysis must take into consideration the geographic context where the crossing is located**
- **Maximum Allowable Unsupported length *should not be the sole criteria* to define risk**
- ***Debris flow* should always be taken into consideration, even in a qualitative way in terms of occurrence or not**

V_i Vulnerability – How fragile?
Free span vs debris flow

V_i Vulnerability – How fragile?

Here goes a video of a mud Flow with floating rocks

M_i Mitigation – How Effective?

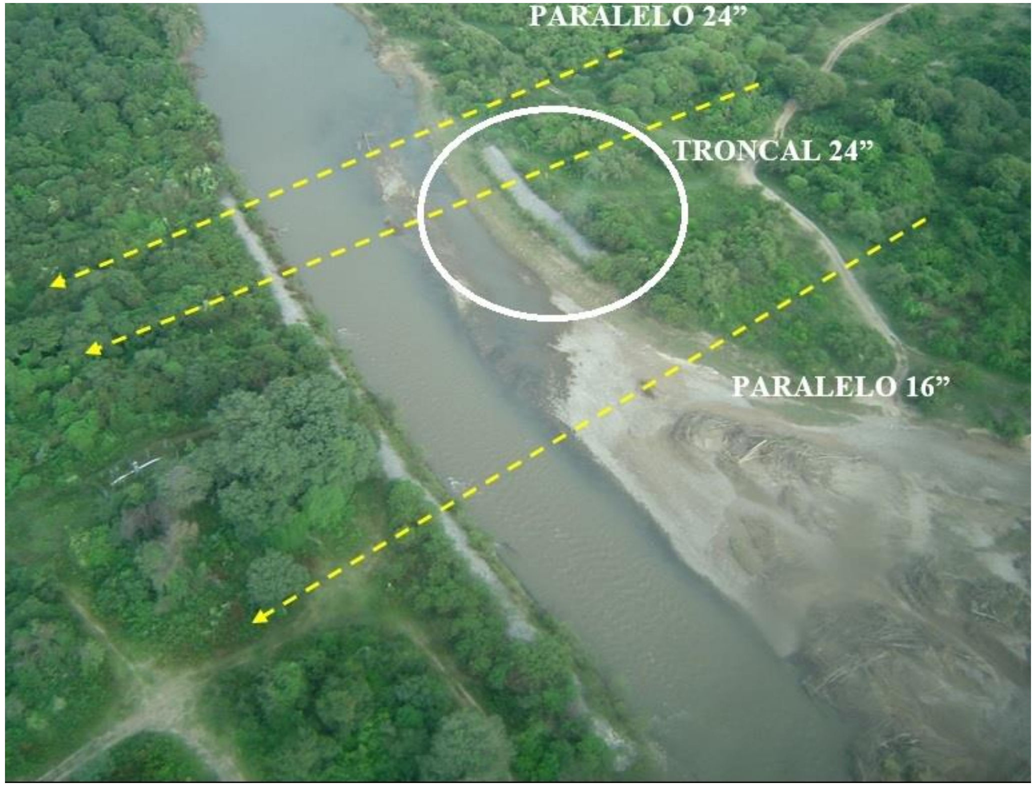


Underrated importance of monitoring:

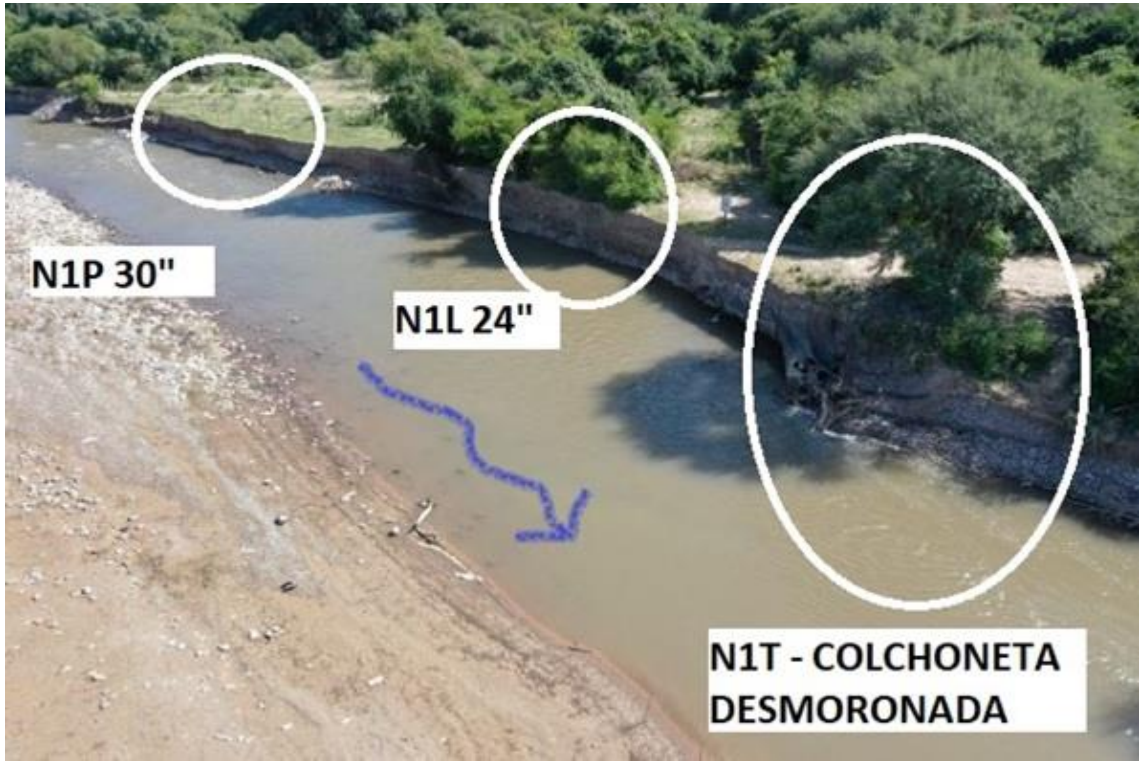
- **Unknown by personnel that collects the information**
- **Key issue when filing a complain to insurance companies (which was the situation prior to an incident?)**
- **Frequency increase as a tool for risk reduction**
- **Extent of remedial works**

M_i Mitigation – How Effective?

Mitigation works built in 2002



Partially collapsed in 2022



Quantitative Risk Analysis and Pipeline Susceptibility
Main Equation: Probability of Failure

After Rizkalla/Read: Pipeline Geohazards Planning, Design, Construction and Operations, ASME

$$S_{Gi} = I_i . F_i . V_i . M_i$$

$$S_{Gi} = 1x0.02x(1x0.1x1)x0.05 = 10^{-4}$$

Compare to Threshold

(Codes & regulations / operator´s policy)

Do I need to implement a remediation work?

Quantitative Risk Analysis and Pipeline Susceptibility

An explanation in plain words must be stated together with the final probability (example):

- Main threat is a combination of vertical and lateral scour at the foot of its left bank, due to river´s own curvature,
- The occurrence of this behavior has been monitored for the past 20 years,
- Exposure of pipeline and its set back is likely to happen in a gradual way,
- When considering a flood that corresponds to a rain storm of a return period of 50 years, stress analysis calculations imply than the affected segment of pipeline is close to the maximum allowable lengths considering drag and vortex induced vibration,
- Existing remediation work still protect this bank, but it is likely to collapse in the nearby future
- New and more comprehensive remediation works are recommended

Quantitative Risk Analysis and Pipeline Susceptibility

- **Can be easily repeated for other return periods once field works and modelling efforts are finished:**

- **Full bank scenario: river flow before flooding (~2 to 5 years),**

- **Intermediate return period such as 10, 25 years used for lesser extent remedial works such one that is aimed to maintain the present situation due to budget restrains,**

- **The usual: 50 to 100 years**

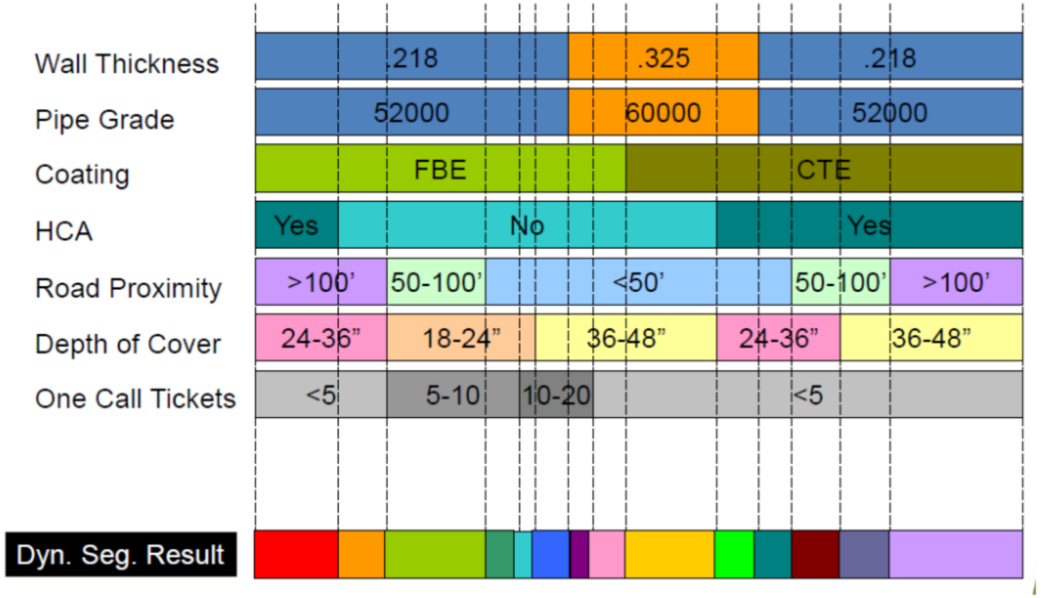
- **Others**

Quantitative Risk Analysis and Pipeline Susceptibility
Integration to Risk Analysis Software
Dynamic segmentation

Data Base → QA/QC information → Data Integración

Dynamic Segmentation

Example considering only a few variables



Hydrotechnical Hazards
Present Challenges

- **Topics for an open discussion**
  - **Development of early warning systems**
  - **Response to emergency**
  - **Calibration of stress analysis calculations under a free-span condition**

Early warning system

- Presentation with focus on ungauged rivers and watersheds
- Relies on mostly daily precipitation
- ***Regional hydrology***:
  - Mean annual precipitation depends on the local hydrological cycle:
    - Atacama desert: 5 to 10 mm per year
    - Peruvian Amazonia: 4000 to 5000 mm per year
    - Argentinian rain forest: 2000 to 3000 per year
    - Patagonian desert: 300 mm per year
  - Rain distribution along a hydrologic year:
    - Rainy and dry season
    - Rain and snowmelt independent peaks
- Triggering rain at TGN: 60 mm in a day and 30 mm for Patagonian desert

Early warning system

- Sources of information:
  - Operator´s own system of meteorological automatic stations,
  - Agencies:
    - Watershed authorities
    - National Meteorological Service
    - Agricultural associations and market operators
    - TV and Social Media

- Actions:
  - Trigger a monitoring trip: terrestrial, drone, aerial (if access is not possible)
  - Personnel safety is an issue during or right after the storm (common concern with Emergency Response)

Early warning system and Pof assessment for a given storm
(~interpolation of actual rain with computed rains of a range of return periods)

- **Existing data from hydrologic modeling**
- **From daily records of rain, obtain a new series of maximum daily precipitation for each year**
- **Statistical prediction of rain from records (Extreme values theory equations: Gauss, Pearson, Gümbel, LogPearson, etc.)**

Compare to actual rain

Return Period [years]	2	5	?	10	25	50	100
Precipitation (from statistics [mm])	91.27	126.13		149.22	178.38	200.02	221.49
Actual daily precipitation [mm]			135				
Pof	10^{-6}	$8x10^{-6}$		$2x10^{-5}$	$8x10^{-5}$	10^{-4}	10^{-3}

Get a feeling of pof

Early warning system and Pof assessment for a given storm
(~interpolation of actual rain with computed rains of a range of return periods)

- This does not imply additional work since its part of a Comprehensive Integrity Study

- Decisions must be made in terms of selecting which and of how many return periods within the scope of the study

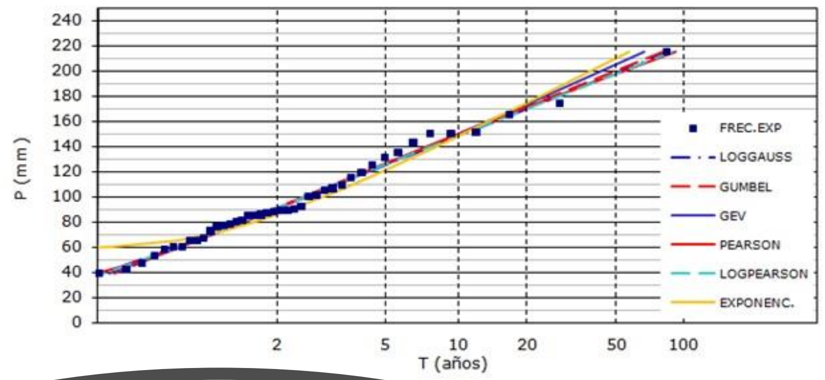
Road from actual rain to net rain to discharge calculation for each return period

Estación	Metan
Parámetro	Precipitación
Serie	Año inicial: 1970 - Año final: 2020
Cantidad años con datos:	42
Operador	SMN

SERIE DE MAXIMOS ANUALES

Año hidrológico		$P_{máx.diaria}$ mm
1970	1971	135.00
1971	1972	92.00
1972	1973	165.00
1973	1974	143.00
1974	1975	100.00
1975	1976	85.00
1976	1977	125.00
1977	1978	215.00
1978	1979	60.00
1979	1980	115.00
1980	1981	89.00
1981	1982	65.00
1982	1983	151.00
1983	1984	77.00
1984	1985	80.00
1985	1986	150.00
1986	1987	87.00
1987	1988	85.00
1988	1989	90.00
1989	1990	150.00
1990	1991	174.00
1991	1992	65.00
1992	1993	60.00
1993	1994	S/D
1994	1995	S/D

Año hidrológico		$P_{máx.diaria}$ mm
1995	1996	S/D
1996	1997	88.00
1997	1998	85.50
1998	1999	S/D
1999	2000	119.00
2000	2001	131.00
2001	2002	81.00
2002	2003	39.00
2003	2004	105.00
2004	2005	47.00
2005	2006	89.00
2006	2007	S/D
2007	2008	S/D
2008	2009	72.50
2009	2010	106.50
2010	2011	S/D
2011	2012	78.00
2012	2013	S/D
2013	2014	76.00
2014	2015	42.00
2015	2016	101.00
2016	2017	67.00
2017	2018	53.00
2018	2019	58.00
2019	2020	109.00



VALORES DE PRECIPITACIÓN DIARIA PARA DISTINTAS RECURRENCIAS Y CÁLCULO PRECIPITACIÓN DE 24 hs

Recurrencia (T)		2	5	10	25	50	100
Pmax	Pdia	91.27	126.13	149.22	178.38	200.02	221.49
$P_{24hs} = P_{diaria} \times FC$	P24h	**103.2**	**142.6**	**168.7**	**201.6**	**226.1**	**250.3**

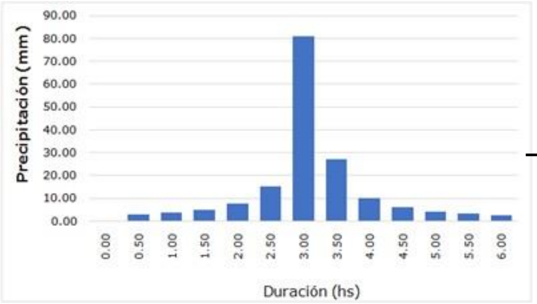
(*) FC= factor de "corrección horaria" - pasaje de Pdiaria a P en 24 hs cualesquiera.

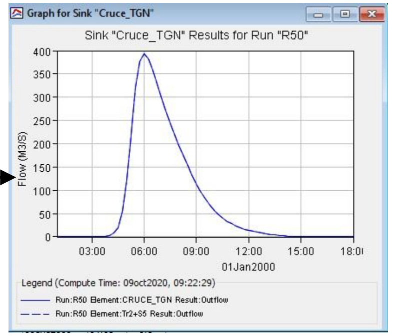
Se adopta Fc= 1.13

r 5min/24h	0.11
r 10min/24h	0.20
r 15min/24h	0.26
r 30min/24h	0.39
r 1/24	0.48
r 2/24	0.65
r 3/24	0.66
r 6/24	0.76
r 12/24	0.90

DETERMINACIÓN CURVA P-D-F EMPLEANDO LAS RELACIONES ANTERIORES

	Tr	PRECIPITACION (mm) PARA DISTINTAS RECURRENCIAS					
t (hs)	t (min)	2	5	10	25	50	100
	5	11.35	15.69	18.56	22.18	24.87	27.53
	10	20.64	28.52	33.74	40.32	45.22	50.06
	15	26.83	37.08	43.86	52.42	58.79	65.08
	30	40.25	55.61	65.79	78.62	88.18	97.62
1	60	49.54	68.45	80.98	96.77	108.53	120.14
2	120	67.08	92.69	109.66	131.04	146.97	162.70
3	180	68.11	94.12	111.34	133.06	149.23	165.20
6	360	78.43	108.38	128.21	153.22	171.84	190.23
12	720	92.88	128.34	151.83	181.44	203.49	225.27
24	**1440**	**103.20**	**142.60**	**168.70**	**201.60**	**226.10**	**250.30**





Response to Emergency

PHMSA–2015–0105 Pipeline Safety
Potential for Damage to Pipeline Facilities Caused by Flooding, River Scour, and River Channel Migration
II. Advisory Bulletin (ADB–2016–01) Pipeline Safety Regulations (49 CFR parts 190–199)

- **List 13 actions to evaluate river crossings (~River Program)**
- **Action 11: Following floods, and when safe river access is first available, determine if flooding has exposed or undermined pipelines because of new river channel profiles. This is best done by a depth of cover survey.**

Response to Emergency-Public Opinion

Questions from the public

DOT Pipeline and Hazardous Materials Safety Administration 49 CFR Part 192, effective May 24, 2023

Section D: Inspections Following Extreme Weather Events

- **Definition of what is an extreme event**
- **Meaning and extent of the word Inspection**
- **Requirement to operators to have procedures to ensure prompt and effective measures**

- **Personal experience: difficulties in explaining the concept of return period**
- **Average time in which a certain extreme event occurs**
- **Exact interval of time for an extreme event to occur**

Response to Emergency

Final Rule:

- **An operator should perform an initial inspection 72 hours (3 days) after the operator reasonably determines that the affected area can be safely accessed by personnel and equipment, and the necessary personnel and equipment to perform such an inspection are available**
- **Allows the operator to consult with other officials in help in this determination,**
- **If the 72 hours limit is not possible to achieve, the operator must notify Regulatory Agencies**

Response to Emergency

Other actions

- ***IMMEDIATE*** **(within hours)**
  - **Reducing operating pressure**
    - **Down to own to what pressure????**
    - **Demands downstream**
    - **Transport commitment according to contracts**
  - **Shutting down the pipeline**
- **OPERATE VALVES**
  - **Manual (again problem with access)**
  - **Remote**

Stress Analysis

- Forces acting on a pipeline in a river crossing
- Selection of method
- Limit criteria
- Calibration against field measurements

Stress Analysis

- Hydrodynamic loads (water flow/Drag force)
- Vortex Induced Fatigue
- Debris impact
- Third party damage (Excavators, Anchors!!,)
- Dead loads (counterweights)
- Loss of support (pipeline own weight)
- Unrestrained/Unrestricted Pipelines supports
- Others (water for hydraulic tests, ILI passage, wind and seism in aerial bridges)

Stress Analysis - Tools

API 1133: Managing Hydrotechnical Hazards for Pipelines Located Onshore or Within Coastal Zone Areas

River-X Software (developed for PRCI)

- Old DOS version
- New version (Don´t know if it and where is available)

Finite Element Method

- **IMPORTANT: how free-span ends are modeled**
  - fixed points,
  - partially restrained
  - Other

Stress Analysis – Limit Criteria

- API 1133: Allowable Stress ***SA = DF x SMYS***
    - Design factor
        - Usually: 0.6 m
        - Avulsion through ROW???
    - Specified Minimum Yield Strength

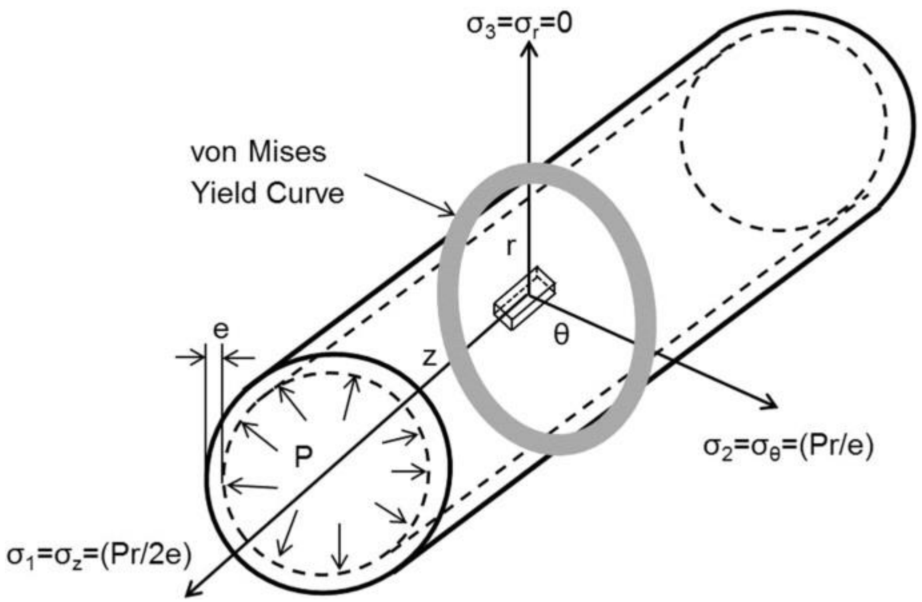
- River-X Software:
    - Old DOS version: Von Misses Stress

von Mises Criterion:

$$Y_p \geq \sigma_{VME} = \frac{1}{\sqrt{2}}\left[(\sigma_z - \sigma_\theta)^2 + (\sigma_\theta - \sigma_r)^2 + (\sigma_r - \sigma_z)^2\right]^{1/2}$$

Where:

Y_p	=	minimum yield strength.
σ_{VME}	=	triaxial stress.
σ_z	=	axial stress.
σ_θ	=	tangential or hoop
σ_r	=	radial stress.



Stress Analysis – Calibration against field measurements

Pipeline Research Council International
Modernize the Assessment of Pipeline Water Crossings project,
Field Validation of VIV Initiation Within Waterways
Prepared by Arcadis US Inc.
Authors: Jeffrey Budzich, Mrinal Verma, Aaron Dayton
March 14, 2022

- **Vibration frequencies were measured in the field by accelerometers placed in a 3" pipe, 0.216" wall thickness, SMYS=35,000 PSi**
- **Comparison against calculated by Finite Element Analysis**
- **Maximum discharges below 1.5 to 2 years of return period**
- **Vortex shedding frequencies were low, cross VIV amplitudes were very small, no detrimental effect on pipeline integrity**
- **Recommends further studies**

¡¡¡Muchas gracias!!!

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