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DESIGN OF HDD INSTALLATIONS USING AMERICAN DESIGN STANDARDS AND LOCALLY MANUFACTURED POLYETHYLENE PIPE

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ABSTRACT: A measure of success of a Horizontal Directional Drilling (HDD) project was once simply pulling the pipe through to the other end of the bore. With improvements in installation technology and contractor capabilities, this should now not be an issue. A measure of success in 2015 for an HDD pipe installation is that the pipe will provide the required asset life. A key aspect of this is that the pipe is appropriately designed for the installation and is not subject to either short or long term loads that exceed its capacity. The American Standard *ASTM F1962-11* is frequently used in Australia and New Zealand for the design of polyethylene pipe HDD installations and provides guidance on how to calculate loads acting on the pipe during and after installation and provides design parameters for different polyethylene pipe materials manufactured to relevant American standards. This paper examines the relevance, appropriateness and adequacy of these pipe parameters and provides recommendations for design using *ASTM F1962-11* with pipe manufactured to the Australian and New Zealand standard *AS/NZS 4130*.

1. INTRODUCTION

Polyethylene (PE) pipes have now existed for over seven decades. In this time they have undergone many developments, not only generation improvement in the pipes themselves but also in extrusion technologies, materials development and engineering know-how. Today the result of this is a wider range of PE pipe applications than ever before. The growing adaptation of trenchless pipeline installation methods is perhaps the latest revolution in the life of the product. With trenchless technologies comes further demand on pipe performance bringing further developments in available PE raw materials and newer generations of PE pipe with improved mechanical properties.

Horizontal Directional Drilling (HDD) is perhaps the most common trenchless installation method involving the installation of PE pipes. Recent advances in installation technology and contractor capabilities mean that more ambitious projects (longer lengths and large diameters) are now becoming commonplace and with an associated high success rate. The obvious question is 'how is this success measured'? At one stage simply pulling the pipe to the other end of the bore would have been considered success. It is suggested that an equally important measure of success is that the installed pipeline continues to adequately perform for its required asset life. For most utilities this would be in the range of 50 – 100 years. An important aspect of this is that the pipe selected is suitable for the range of loading conditions that it will be subject to during both the installation (temporary loads) and in service (permanent loads) conditions.

Existing Australian and New Zealand Standards that are relevant to the design and installation of PE pipelines, *AS/NZS 4130* (Standards Australia and Standards New Zealand, 2009), *AS/NZS 2566.1* (Standards Australia and Standards New Zealand, 1998), *AS/NZS 2566.2* (Standards Australia and Standards New Zealand, 2002) and

AS/NZS 2033 (Standards Australia and Standards New Zealand , 2008), provide at best very limited guidelines for pipe selection or design for pipelines installed using HDD or other trenchless methods. For example:

- *AS/NZS 2566.1* states that it "*does not give design guidelines for bored, jacked or mole ploughed installations*"; and
- *AS/NZS 2033* states that "*Trenchless technology may be adopted by methods such as directional drilling, thrust-boring, micro-tunnelling and pipe jacking. NOTE: For further information refer to www.astt.com.au (see Appendix A)."*

In the absence of adequate guidelines in local standards, designers in Australia and New Zealand have little choice other than to use other relevant overseas standards. One such standard often used is *ASTM F1962* (ASTM, 2011). This standard is a guide and provides substantial information regarding the design, selection considerations and installation procedures for installation of PE pipe using "Maxi-Horizontal Directional Drilling". Included in this standard are recommended design parameters for different PE pipe materials manufactured to relevant American (typically ASTM) standards. This paper examines the origin and appropriateness of these design parameters for PE manufactured in accordance with the relevant local standard *AS/NZS 4130* (Standards Australia and Standards New Zealand, 2009) and provides suggestions for similar design parameters for this pipe.

2. BRIEF HISTORY OF DEVELOPMENT OF PE PIPE IN AUSTRALIA AND NEW ZEALAND

Though polyethylene pipes have been manufactured and used in Australia for over 50 years, the development of polyethylene came in England quite by chance in 1933. European post-war reconstruction after 1945 saw the adaptation of polyethylene as a pipe material in the form of LDPE (Low Density Polyethylene). The mechanical properties of PE materials advanced making it suitable for a wide range of applications and it soon became a preferred pipeline material. In particular from the 1970s in Europe and the 1980s in Australia and New Zealand, it firmly established its place in the market and has often become the preferred material of choice for pipelines in gas, water and various other fields.

Initial variants of polyethylene pipes were homopolymeric LDPEs. Later came HDPE (High Density Polyethylene). HDPE, having a different molecular structure with a greater degree of crystallinity and density relative to LDPE, came to be classified by the nomenclature Type 50 and Type 63 which reflected the MRS (Minimum Required Strength) values of the material; these being 5.0 MPa and 6.3 MPa respectively. Copolymer molecular structures were also developed by way of introducing an additional olefin that disturbed the pattern of linear molecular chains by creating tie-ins between the molecular chains resulting in improved properties (Callister, 2003).

The late 1980s saw further developments in raw materials and the introduction of PE 80B MDPE (Medium Density Polyethylene) and PE 80C with an MRS value of 8.0MPa. Further enhancements came in the late 1990s with the widespread acceptance of bimodal PE 100 material, a higher density variant relative to PE80, with enhanced mechanical properties including ESCR (Environmental Stress Crack Resistance), SCG (Slow Crack Growth) and improved toughness, all of which are essential for trenchless installations such as HDD and sliplining.

Concurrent with the development of the pipe materials were the standards governing the pipes, the pipe fittings and the recommendations for installation and design. Initially by way of *AS 2033* in 1980 for installation, followed by the comprehensive *AS/NZS 4130* for PE pipe and *AS/NZS 4129* for PE pipe fittings. Another industry norm heavily relied upon for PE pipelines, and also other flexible pipelines, are *AS/NZS 2566.1*, Buried Flexible Pipelines: Part 1 Design and *AS/NZS 2566.2* Buried Flexible Pipelines: Part 2 Installation. Together these standards represent the metaphoric toolbox for all things related to PE pipeline design and construction in Australia and New Zealand. However, comprehensive as they are, they fail to provide any real guidance for the rapidly evolving field of trenchless construction and the various methods that trenchless construction may involve.

3. SUMMARY OF ASTM F1962 DESIGN METHODOLOGY

A detailed explanation of the contents of *ASTM F1962* is beyond the scope of this paper but the following is a very brief summary of the most relevant aspects of this standard that relate to pipe selection. The title of *ASTM F1962* is *Standard Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene*

Pipe or Conduit Under Obstacles, Including River Crossings. It defines Maxi-Horizontal Directional Drilling as:

> *a class of HDD, sometimes referred to as directional drilling, for boring of holes of up to several thousand feet in length and placing pipes of up to 48 in. (1¼ m) diameter or greater at depths of up to 200 ft (60 m).*

It provides a guide to a number of issues associated with the planning, design and construction of larger HDD installations. In terms of pipe design and selection it includes:

- Guidelines for calculation of both operational (long term) and installation (short term) loads.
- A methodology for calulating pipe deflection due to earth loads, buoyancy and longitudinal bending.
- A methodology for calculating an allowable collapse pressure excluding tensile loads.
- A methodology for calculating bending stresses due to curvature of the installation.
- A methodology for calculating pulling forces and associated axial tensile stresses.
- A methodology for calculating an allowable collapse pressure including tensile loads.

3. PE PIPE PROPERTIES IN ASTM F1962

3.1 PE Pipe Designation

Appendix X1.1 of *ASTM F1962* includes typical Apparent Modulus of Elasticity and Typical Safe Pull Stress values for both HDPE (PE3408) and MDPE (PE2406) resins. Designers in Australia or New Zealand may be familiar with the terms HDPE and MDPE but most would not be familiar with PE3408 or PE2406. What do these mean?

ASTM standards use a numerical system for resin identification. *ASTM D3350* (ASTM , 2014) uses a cell classification system that identifies six properties that are considered important in the manufacture of PE piping. These properties are:

1. Density of PE base resin.
2. Melt Index of compound.
3. Flexural Modulus of compound.
4. Tensile Strength at Yield of compound.
5. Resistance to Slow Crack Growth of compound.
6. Hydrostatic Strength Classification expresses either as a Hydrostatic Design Basis for water at 23°C or Minimum Required Strength at 20°C.

Chapter 5 of the Handbook of Polyethylene Pipes (PPI, 2007) included an example of a PE pipe having a designation code PE445574C where each of the numerical digits identified a property from Table 1 of *ASTM D3350*.

A simpler short-hand material designation code is however used in PE piping standards such as *ASTM F714* (ASTM, 2013). This simpler designation is detailed in the Chapter 5 of Handbook of Polyethylene Pipes (PPI, 2007) and is summarised as follows for the compound PE 3408 listed in *ASTM F1962*:

- PE is the ASTM recognised abbreviation for polyethylene.
- The first digit (3) identifies the density range of the base PE resin in accordance with *ASTM D3350*.
- The second digit (4) identifies the compound’s resistance to slow crack growth (SCG) in accordance with *ASTM D3350*.
- The last two digits (08) identify the compound’s maximum recommended hydrostatic design stress (HDS) category for water at 73°F (23°C) for which the 08 refers to a HDS of 800 psi (5.5 MPa).

3.2 Safe Pulling Stress

Table X1.1 of *ASTM F1962* (ASTM, 2011) contains values for safe pulling stress (SPS) for compounds PE3408 and PE2406 for different pulling durations. The standard does not detail or reference where these values came from but it seems reasonable to conclude that the same or similar methodology contained in *ASTM F1804* (ASTM, 2012) has been applied to obtain these values. The allowable tensile load is defined in Equation (1) of *ASTM F1804* as follows:

$$ATL = f_y.f_t.T_y.\pi.D^2.[\frac{1}{R} - \frac{1}{R^2}] \quad (1)$$

Where:

ATL = allowable tensile load, lb (N)

f_y = tensile yield design (safety) factor. *ASTM F1804* states that this factor is usually 0.5 or less. If a design safety factor is not available from the pipe manufacturer a value of 0.4 is used.

f_t = time under tension design (safety) factor. Based on 5% strain, *ASTM F1804* recommends safety factors of 1.00 for time to 1 h, 0.95 for times to 12 h, and 0.91 for times to 24 h.

T_y = Tensile yield strength, psi (MPa), of the polyethylene pipe material at the pipe installation temperature. *ASTM F1804* states that for installation temperatures of 100^{0}F (38^{0}C) or less, use tensile yield strengths of 2600 psi (18 MPa) for PE2406, PE2606 or PE2708 or 3000 psi (21 MPa) for PE3408, PE3608, PE3710, PE4608 and PE4710 or a value from the pipe manufacturer or from pipe material sample testing.

D = Pipe outside diameter, in. (m)

R = Pipe dimension ratio.

Ignoring the geometric / dimensional values it is possible to calculate a maximum stress value using the first part of Equation 1 ($f_y.f_1.T_y$). Table 1 contains the results of this calculation for a value of f_y = 0.4 for the compound PE3408 (T_y = 3000 psi).

Table 1- Calculation of Safe Pulling Stress for PE3408 to ASTM F1804.

Pull Time (h)	f_t	f_y	T_y (psi)	$f_1.f_y.T_y$ (psi)	$f_1.f_y.T_y$ (MPa)
1	1	0.4	3000	1200	8.3
10	0.95	0.4	3000	1140	7.9
24	0.91	0.4	3000	1092	7.5

If the values in column 5 of Table 1 were rounded up to the nearest 50 psi, as recommended by *ASTM F1804*, the same values for a Safe Pulling Stress are contained in Table X1.1 of *ASTM F1962* are obtained for PE3408. The same results were not obtained for PE2406 using the recommended parameters of *ASTM F1804* as can be seen in Table 2.

Table 2 - Calculation of Safe Pulling Stress for PE2406 to ASTM F1804.

Pull Time (h)	f_1	f_y	T_y (psi)	$f_1.f_y.T_y$ (psi)	$f_1.f_y.T_y$ (MPa)
1	1	0.4	2600	1040	7.2
10	0.95	0.4	2600	988	6.8
24	0.91	0.4	2600	946	6.5

Whilst there appears to be some inconsistency between *ASTM F1804* and *ASTM F1962*, it seems reasonable to assume that the safe pull stress values contained in Table X1.1 of *ASTM F1962* are based on the tensile yield strength of the polyethylene compound. *ASTM F1804* states that the tensile yield strength is to be determined in accordance with *ASTM D638* (ASTM, 2010).

3.3 Apparent Modulus of Elasticity

Table X1.1 of ASTM F1962 also contains typical values for the Apparent Modulus of Elasticity (E or E_a) for compounds PE3408 and PE2406 for different durations. This parameter is used in *ASTM F1962* in the calculation of:

(a) The allowable external collapse pressure (P_{ua}) in Equation 5.

(b) The axial bending stress (σ_a) due to pipeline curvature in Equation 7.

(c) The allowable collapse pressure (P_{pba}) due to the presence of axial tensile load in Equation 22.

ASTM F1962 does not define the term Apparent Modulus of Elasticity nor does it provide references for the origin of the values contained in Table X1.1.

Chapter 3 of the Handbook of Polyethylene Pipe (PPI, 2007, pp. 57-63) explains the term apparent modulus in terms of the viscoelastic (part viscous and part elastic) nature of polyethylene. The term apparent is used to distinguish it from a modulus of elasticity for a purely elastic material. The Handbook of Polyethylene Pipe (PPI, 2007) goes on to explain that the value of the apparent modulus depends on a number of factors but most importantly the duration of loading, the stress intensity, the nature of the applied stress (i.e. uniaxial or biaxial) and temperature. Table B1.1.1 of Chapter 3 of the Handbook of Polyethylene Pipe (PPI, 2007, p. 99) includes design values of the Apparent Elastic Modulus which is replicated as Figure 1 below. It also states that:

> *There is one kind of operation that results in a temporary tensile stress that is significantly beyond the maximum range of 300-400 psi for which Table B.1.1. applies. This is an installation by pipe pulling, a procedure that is the subject of Chapter 12. At the significantly greater uni-axial stresses that result under this installation procedure, the resultant apparent modulus is about 2/3rds of the values that are listed in Table B.1.1.*

It is interesting to note that Table 2 of Chapter 12 of the Handbook of Polyethylene Pipe, Horizontal Directional Drilling (PPI, 2007, p. 427), includes exactly the same values for both Apparent Modulus and SPS that are in Table X1.1 of *ASTM F1962*.

TABLE B.1.1
Apparent Elastic Modulus for 73°F (23°C)

Duration of Sustained Loading	Design Values For 73°F (23°C) [1,2,3]					
	PE 2XXX		PE3XXX		PE4XXX	
	psi	MPa	psi	MPa	psi	MPa
0.5hr	62,000	428	78,000	538	82,000	565
1hr	59,000	407	74,000	510	78,000	538
2hr	57,000	393	71,000	490	74,000	510
10hr	50,000	345	62,000	428	65,000	448
12hr	48,000	331	60,000	414	63,000	434
24hr	46,000	317	57,000	393	60,000	414
100hr	42,000	290	52,000	359	55,000	379
1,000hr	35,000	241	44,000	303	46,000	317
1 year	30,000	207	38,000	262	40,000	276
10 years	26,000	179	32,000	221	34,000	234
50 years	22,000	152	28,000	193	29,000	200
100 years	21,000	145	27,000	186	28,000	193

(1) Although there are various factors that determine the exact apparent modulus response of a PE, a major factor is its ratio of crystalline to amorphous content – a parameter that is reflected by a PE's density. Hence, the major headings PE2XXX, PE3XXX and, PE4XXX, which are based on PE's Standard Designation Code. The first numeral of this code denotes the PE's density category in accordance with ASTM D3350 (An explanation of this code is presented in Chapter 5).

(2) The values in this table are applicable to both the condition of sustained and constant loading (under which the resultant strain increases with increased duration of loading) and that of constant strain (under which an initially generated stress gradually relaxes with increased time).

(3) The design values in this table are based on results obtained under uni-axial loading, such as occurs in a test bar that is being subjected to a pulling load. When a PE is subjected to multi-axial stressing its strain response is inhibited, which results in a somewhat higher apparent modulus. For example, the apparent modulus of a PE pipe that is subjected to internal hydrostatic pressure – a condition that induces bi-axial stressing – is about 25% greater than that reported by this table. Thus, the Uni-axial condition represents a conservative estimate of the value that is achieved in most applications.

It should also be kept in mind that these values are for the condition of continually sustained loading. If there is an interruption or a decrease in the loading this, effectively, results in a somewhat larger modulus.

In addition, the values in this table apply to a stress intensity ranging up to about 400psi, a value that is seldom exceeded under normal service conditions.

Figure 1 - Extract Handbook of Polyethylene Pipe Handbook (PPI, 2007, p. 99)

A comparison between the modulus values contained in Table X1.1 of *ASTM F1962* and corresponding values from Table B.1.1. of the Polyethylene Pipe Handbook is presented in Table 3. This table also contains the latter values reduced by a factor of 2/3rds as recommended. As can be seen in Table 3 there is reasonable agreement between the values of Apparent Elastic Modulus contained in Table X1.1 of *ASTM F1962* and Table B.1.1 of the PPI handbook, sufficient to reasonably conclude that the values contained in *ASTM F1962* are based on a uniaxial tensile test. The only significant differences are the "Short-term" values where *ASTM F1962* uses the term "Short-term" and the PPI values are at 0.5 hours. The PPI values reduced by a factor of 2/3 are lower for obvious reasons. These latter values have been included for comparison purposes only and it is not recommended that they necessarily be used. Note 3 of Table B.1.1 of the PPI Handbook probably provides both a guide and caution to using results from a simple uniaxial tension test to a far more complex loading situation that the HDD installation may involve.

Table 3 - Comparison ASTM F1962 and PPI Apparent Elastic Modulus Values at 73°F (23°C)

	Table X1.1 ASTM F1962 psi [MPa]		**Table B.1.1 PPH* psi [MPa]**		**Table B.1.1 PPH* x 2/3 psi [MPa]**	
Duration	**HDPE**	**MDPE**	**PE3XXX**	**PE2XXX**	**PE3XXX**	**PE2XXX**
Short-term	110 000 [800]	87 000 [600]	78 000 [538]	62 000 [428]	52 000 [360]	41 300 [285]
10 h	57 500 [400]	43 500 [300]	62 000 [428]	50 000 [345]	41 300 [240]	33 300 [230]
100 h	51 200 [350]	36 200 [250]	52 000 [359]	42 000 [290]	34 700 [240]	28 000 [190]
50 years	28 200 [200]	21 700 [150]	28 000 [193]	22 000 [152]	18 700 [130]	14 700 [100]
* = Polyethylene Pipe Handbook (PPI, 2007)						

It is also worth repeating that the value of the Apparent Elastic Modulus (E_a) is used in multiple locations in *ASTM F1962* which involve different durations and loading situations. For example in Equation (7) of *ASTM F1962*, E_a is used to calculate a stress resulting from bending of the pipe. Adopting a lower value of E_a in this case would result in a lower stress and as such would not be conservative. Similarly an apparent modulus value is included in formulae (Equations 5 and 22) for the calculation of allowable collapse (buckling) pressures under different loading conditions. How relevant a value of a modulus obtained from a tensile test is to what is essentially a ring buckling problem is questioned, however exploring this issue further is beyond the scope of this paper.

4. MATERIAL PROPERTIES OF PIPE TO AS/NZS 4130 AND AS/NZS 4131.

Polyethylene pipe used for HDD installations in Australia and New Zealand will almost certainly comply with the requirements of *AS/NZS 4130* (Standards Australia and Standards New Zealand, 2009). Pipes to this standard would be manufactured from polyethylene compounds (PE 80 or PE 100) complying with the requirements of *AS/NZS 4131* (Standards Australia and Standards New Zealand, 2010). *AS/NZS 4130* includes dimensions for Series 1 (water) and Series 2 & 3 (gas) pipes.

For a designer of an HDD installation specifying PE pipe to *AS/NZS 4130* what then are the pipe mechanical properties that may be relevant to the design of the pipe to *ASTM F1962*? Based on the contents of both *AS/NZS 4130* and *AS/NZS 4131* the designer would know the following mechanical properties of the pipe being used in the installation:

- Series 1 pipe (general pressure applications) dimensions are based on a hydrostatic design stress (HDS) of 6.3 and 8.0 MPa (C = 1.25) for PE 80 and PE 100 respectively – foreword of *AS/NZS 4130:2009*.
- Pipe intended for transmission of fuel gas would be suitable for operation up to a maximum allowable operating pressure (MAOP) of 1050 kPa.
- When tested in accordance with *AS/NZS 1462.6* (Standards Australia and Standards New Zealand, 2006) at 80°C pipes would sustain a minimum applied internal pressure - clause 10.1 of *AS/NZS 4130:2009* and clause 7 of *AS/NZS 4131:2010*.
- Pipes would meet a minimum requirement for slow crack growth resistance – clause 10.4 of *AS/NZS 4130:2009* and clause 8 of *AS/NZS 4131:2010*.
- PE80 and PE 100 would have a minimum required strength (MRS) of 8.0 and 10.0 MPa respectively – Clause 6.1 of *AS/NZS 4131:2010*.

- Pipes would meet a minimum requirement for rapid crack propagation resistance – clause 6.2 of *AS/NZS 4131:2010*.

All of the above listed properties are important and appropriate with regards the design of the pipeline for permanent loads, most notably internal pressure. These properties however offer little guidance to the designer of the HDD installation who will be most interested mainly in the tensile strength and elastic modulus.

In the absence of the required design parameters in the existing AS/NZS standards, designers could then consult the pipe manufacturer directly. Two leading Australian manufacturers do publish the relevant typical properties on their websites and these are included in Table 4.

Table 4 – PE Material Properties from Australian Manufacturers

Manufacturer	Property	Units	Test Method	PE80B	PE 100
Vinidex[1]	Tensile Yield Strength	MPa	ISO 527	20	23
Vinidex	Elongation at Yield	%	ISO 527	10	8
Vinidex	Tensile Modulus – short term	MPa	ref. AS/NZS 2566.1	700	950
Vinidex	Tensile Modulus – long term	MPa	ref. AS/NZS 2566.1	200	260
Iplex[2]	Tensile Yield Stress (50 mm/min)	MPa	-	20	25
Iplex	Tensile Yield Strain (50 mm/min)	%	-	8	10
Iplex	Tensile Modulus	MPa	-	650	900

Notes to Table 4:

1. Source Vinidex Pty Ltd website: www.vinidex.com.au.
2. Source Iplex Pipelines Australia Pty Ltd website: www.iplex.com.au.

It is interesting to note the two values of tensile strength quoted by the two manufacturers particularly for PE 100 which is probably the most commonly used material for HDD installations in Australia and New Zealand. The two values of 23 and 25 MPa are greater than the maximum higher recommended yield stress values recommended in *ASTM F1804* at 21 MPa. The ASTM quoted figures are at 38 ºC and the figures in Table 4 are likely to be at the *ISO 527* recommended temperature of 23 ºC.

It is difficult to make any direct comparison between the modulus values contained in Table 4 and the values for the Apparent Elastic Modulus of Elasticity values contained in Table X1.1 of *ASTM F1962*. The values quoted by Vinidex appear to be ring bending modulus values from *AS/NZS 2566.1*. It is assumed the values quoted by Iplex are "short-term" values and if so compare reasonably well with the short-term values in Table X1.1.

It is understood most PE pipe manufacturers obtain resin from a small group of suppliers. In Australia Qenos is a major supplier of resin for PE pipe manufacture. Qenos (www.qenos.com.au) provide significant technical literature for different resins and PE in general. This paper has focused significantly on yield strength of PE but it is worth briefly discussing the post yield behaviour. Figure 2 is an extract from the Qenos Technical Guide TG7 (Qenos Pty. Ltd., 2014) for its Alkadyne compounds and shows a typical stress / strain curve for a PE 100 type compound. It should be noted that the end of the curve represents the ultimate failure of the test specimen. As such it should be noted that using an ultimate strength value for a PE compound is a meaningless term due to the extremely high strain at failure. Any suggestion that a measure of success may be the pipe not "breaking" is an absurd concept.

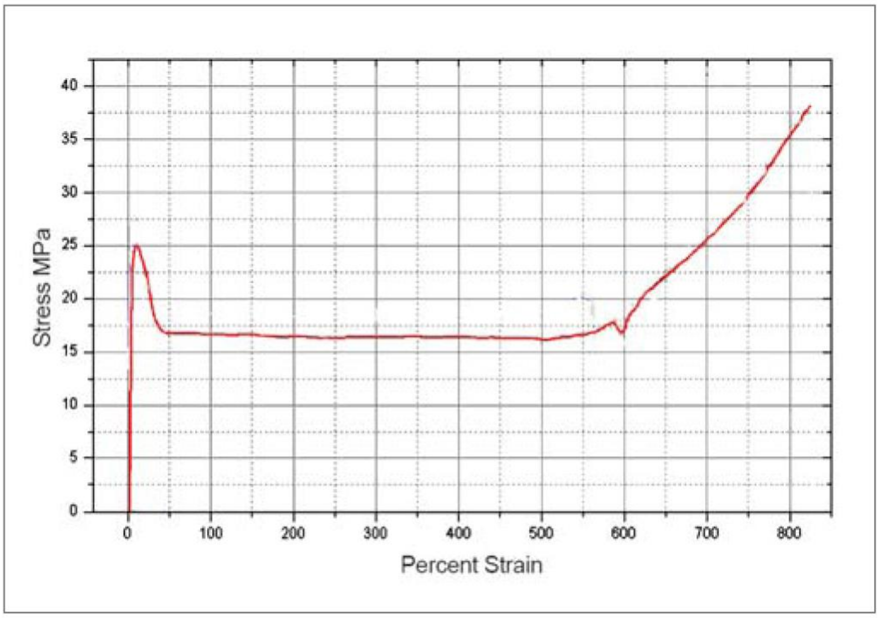

Figure 15: Typical Stress/Strain Curves for HDPE Measured in a Tensile Test on Test Specimen Prepared from Compression Moulded Sheet; Test Temperature 23°C, Testing Rate 50 mm/min

Figure 2 - Typical Stress / Strain Curve for PE 100 Type Material (www.qenos.com)

5. COMPARISON ASTM & AS/NZS REQUIREMENTS

5.1 Hydrostatic Strength

Throughout this paper reference has been made to various terms related to the capacity of a PE pipe to sustain internal hydrostatic pressure. Here there is a fundamental difference between ASTM and AS/NZS standards with the latter largely based on requirements of ISO (International Organisation for Standardization) standards. ASTM standards require a Hydrostatic Design Basis (HDB) to be determined in accordance with *ASTM D2837* (ASTM, 2013) from which a Hydrostatic Design Stress (HDS) is obtained using an appropriate Design Factor (DF) such that:

$$HDS \; = \; HDB \; x \; DF \tag{2}$$

AS/NZS 4131:2010 requires that the long-term hydrostatic strength of pipe compounds is evaluated in accordance with *AS/NZS 1462.29* (Standards Australia and Standards New Zealand, 2006) which is largely a reprint of *ISO 9080* (International Organisation for Standardization, 2012). *ISO 9080* requires that a Minimum Required Strength (MRS) is determined from which a Hydrostatic Design Stress (HDS) is obtained using an appropriate Design Coefficient (C) from *ISO 12162* (International Organisation for Standardization, 2009) such that:

$$HDS = \frac{MRS}{C} \tag{3}$$

A more complete explanation of the differences between the ASTM and ISO methods is detailed in the PPI publication TR-9/2022 (Plastics Pipe Institute, 2002). This publication concludes that the "*HDB and MRS are different methods for predicting material performance, and it is possible for the calculated pressure rating to be different if both methods are used for the same material*." This comparison is also further explained in the PPI publication TN-28/2014 (Plastics Pipe Institute, 2015). It states that *"some PE 4710 compounds can be rated as PE 100 or PE80 under the ISO protocol, and some PE 100 compounds can be rated as either PE 4710 or PE 3408 when evaluated within the context of the ASTM/PPI protocol"*.

The hydrostatic strength, by whichever method it is determined, is obviously an indirect measurement of the tensile strength of the pipe material, but as the methods for determining the capacity are different between ASTM and AS/NZS standards a direct comparison is of limited value and as such has not been considered further in this paper.

5.2 Tensile Strength and Elastic Modulus

These are the two parameters the designer of the HDD installation is most interested in. However like the hydrostatic strength, there are different standards and different approaches between the relevant ASTM and ISO test methods which means that a direct comparison between values obtained by the different methods are of limited value. *ASTM D638-14* (ASTM, 2014) is the relevant ASTM standard for determination of both the tensile strength and the elastic modulus. The relevant ISO standard has several parts but the general principles are contained in *ISO 527-1* (International Organisation for Standardization, 2012). There are a number of differences between the test procedures of the relevant standards including the sample preparation, the prestressing of the specimen and the rate of loading.

6. CONSTRUCTION RELATED ISSUES

The bulk of this paper has been very much related to the design of PE pipe and appropriate design parameters for this pipe. This aspect of the design is largely related to a very short term activity, the day of the pipe pull. As such it is important to include construction related issues relevant to the design that may have been carried out. The following is a brief summary of some of the main construction related issues.

6.1 What is the likelihood of a pipe being overstressed during installation?

With larger projects being attempted and larger equipment being available, the likelihood that a pipe may be subject to axial stress in excess of a safe pull stress is "Possible" to use risk management terminology. The information contained in Table 5 is from an actual project and contains a summary of the HDD rig pull capacities for a number of different tenderers, safe pulling force and pulling force required to achieve pipe yield. As can be seen the rig pull capacities generally were well in excess of the safe pipe pulling forces adopting the 12 hour value of SPS from Table X1.1 from *ASTM F1962*. In this example the rig capacities were generally well in excess of the pipe "safe" capacity and even the yield strength of the pipe. It is likely, however, that the pipe would not be overstressed in a well-conditioned bore hole as there would be insufficient reaction generated from pulling the pipe for the rig to generate such a force. In this example the calculated maximum pulling stress was just under the safe pulling stress for an empty pipe and well under it for a water ballasted pipe.

Table 5 - Case Study Rig vs Pipe Capacity

Pipe Details	DN500	PE 100	PN20	SDR9		
Pipe Safe Pull Force (7.9 MPa SPS)	646	kN	66	tonnes		
Pipe "Yield Force" (25 MPa Stress)	2043	kN	208	tonnes		
Tenderer	1	2	3	4	5	6
Rig Pull Capacity (lbs)	330,000	492,103	100,000	492,103	492,103	1,000,000
Rig Pull Capacity (ton)	147	246	45	246	246	500
Rig Pull Capacity (tonne)	150	250	45	250	250	508
Rig Pull Capacity (kN)	1468	2453	445	2453	2453	4984
Rig Capacity/Pipe Capacity (SPS) (%)	227%	380%	69%	380%	380%	772%
Rig Capacity/Pipe Yield (%)	72%	120%	22%	120%	120%	244%

6.2 What are the consequences of a pipe being overstressed?

Overstressed would involve the pipe being subject to tensile stresses in excess of the safe pulling stress (SPS). If this involved a stress approaching the yield stress then it is likely that this would be completely unacceptable depending on the intended use of the asset. The consequences of a pipe being subject to a tensile stress in between the SPS and yield is beyond the scope of this paper other than to say the best remedy is prevention.

6.3 How can you prevent a pipe from being overstressed?

There are a number of measures that could be considered for different projects. It is suggested that the starting point should always be a calculation of the estimated pulling forces and associated pipe stresses. These calculations would then normally be used to either check or select an appropriate pipe wall thickness (SDR). Once this is done there are a number of controls that can be put in place during installation. These include:

- *Water ballasting.* This is less of a control measure and more of a measure to reduce the pulling force by reducing the friction between the pipe and the bore. In the example quoted above the use of water ballasting reduced the calculated maximum pulling stress by approximatley 50%. This also greater assists with the prevention of buckling which often controls the design.
- *Monitoring pulling force at the drill rig.* This is probably the most common method of control but has limitations with the main one being that the force being monitored is the force at the rig and not at the pipe pulling head. It is too conservative to apply the maximum allowable pulling force of the pipe to the force applied at the rig. Forces associated with a final reaming pass should be recorded and these can then be used to estimate the pulling force at the pulling head during installation. Another potential issue is calibraiton of the force measuring system at the rig.
- *Using "break-away links".* These are often referred to in American publications and *ASTM F1962* states that these should be set at the allowable tensile load of the pipe. These break-away links are designed to fail and hence the pipe will either have to be pulled back from the pipe entry end or abandoning the installation. These are not favoured by local contractors. An argument often put forward is the links may fail very close to the end and it may then be almost impossible to pull the pipe back to the entry side. More work needs to be done on this, but setting break-away links at say 60 - 75% of pipe yield may be a "reasonable" approach.
- *Using a smart pulling head.* Such units involve real time monitoring of pulling force at the pulling head and downhole fluid pressures. It is understood such devices are available and involve a wireless connection back to the surface.

6.4 Installation Temperature

The mechanical properties of a pipe contained in Table X1.1 of ASTM 1962 are for a temperature of 73 ^{o}F or 23 ^{o}C. Using these properties for a pipe that has been sitting out in the sun particularly in northern Australia is unlikely to be appropriate. For this reason pipe pulling should always commence early in the morning after the pipe has had a chance to cool overnight. Whilst this may be stating the obvious it is important to not lose sight of this reason.

7. CONCLUSIONS AND RECOMMENDATIONS

This paper has set out to determine the appropriateness and adequacy of a number of pipe mechanical properties contained in *ASTM F1962* for pipe manufactured to *AS/NZS 4130*. In order to examine this, the likely origin of these properties has also been explored.

The safe pulling stress (SPS) is probably the most fundamental property contained in *ASTM F1962* and it has been suggested that the origin of the values contained in *ASTM F1962* can be found in *ASTM F1804*. Specifically it has been found that the values for HDPE pipe contained in *ASTM F1962* can be obtained by applying a Tensile Yield Design (Safety) Factor of 0.4 (f_Y in F1804) and a time under tension design (safety) factor (f_t in F1804) to a Tensile Yield Strength (T_y in F1804) of 3000 psi (21 MPa) where the yield strength is determined in accordance with *ASTM Test Method D638*.

The Apparent Modulus of Elasticity is the other key pipe mechanical property that is used in the design method contained on *ASTM F1962*. Again, the origin of the values contained in *ASTM F1962* appears to be the results of uniaxial tensile testing of different polyethylene compounds.

The identification of polyethylene pipe in both ASTM and AS/NZS standards has been explained. An attempt has also been made to make a direct comparison between different compounds listed in *ASTM F1962* (PE2406 and PE3408) and those in *AS/NZS 4130* (PE80 and PE 100) but this has proved difficult due largely to a fundamental difference between ASTM and largely ISO test methods.

The properties of polyethylene compounds and PE pipe manufactured in accordance with the relevant AS/NZS standards have also been explained. There is no requirement for a minimum tensile strength included in these standards and as such if a designer needs to know this value the pipe manufacturer should be consulted. A brief review of published (websites) tensile strength values for some Australian pipe manufacturers was carried out and it was found that the tensile strength of PE 100 is higher than what has been suggested was used in ASTM F1962 as the basis of determination of safe pulling stresses for HDPE (PE3408). It is therefore concluded that the values of SPS contained in *ASTM F1962* for HDPE pipe are appropriate to use for PE 100 pipe to *AS/NZS 4130* and are possibly even conservative.

The Apparent Modulus of Elasticity values for locally manufactured pipe have not been explored in much detail. This is potentially a complex subject and it was questioned how appropriate the use of modulus values obtained from tensile testing were to all uses of this parameter in *ASTM F1962*.

The post yield behaviour of a typical PE 100 compound was presented. Whilst somewhat beyond the scope of this paper it was considered important to highlight what the typical post yield behaviour of a PE pipe (PE 100) looks like and how irrelevant the ultimate failure of the pipe is when considering success criteria.

Finally the paper looked at a number of construction related issues and demonstrated that the potential for overstressing a pipe is real as longer length projects with larger rigs are attempted.

As a result of these investigations, this paper finds that the application of *ASTM F1962* is appropriate for design of HDD systems using Australian and New Zealand manufactured PE pipe.

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