Sub-atmospheric transient pressure conditions – where and what it may influence in design

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Abstract

In the analysis of hydraulic transient conditions, practitioners are often primarily concerned about the maximum or upsurge pressure condition within the pipeline system. If the upsurge condition is within the tolerances of the local (specified) pipeline standard then the pipeline is regarded to be suitable for safe, reliable service. However, transient pressures are waves and when there is an upsurge event all but inevitably, there will be or there has been a significant downsurge event. Through performance and review of innumerable transient analyses and corresponding pipeline designs, the authors can generally say that practitioners (design engineers) do not consider the structural consequences of a full vacuum condition problematic. As a result, in pipeline design, rarely are downsurge or sub-atmospheric transient pressure conditions comprehensively considered. This paper documents how and where downsurge pressures are used in a standard design process and identifies areas where hydraulic transient analyses could be used to refine and potentially improve pipeline designs by introducing a consideration of dynamic loading characteristics into the pipeline design process. The paper also considers the current pipeline design process and how it addresses hydraulic transient pressure conditions with regard to the pipeline's lining and joint systems. Finally, as supported by the paucity of published research and the ambiguity of the applicable standards, a summary of pertinent and relevant questions are posed. These questions are then used to outline additional research efforts that will allow a better consideration of hydraulic transient loading conditions, namely sub-atmospheric transient pressure conditions, within conveyance pipeline design procedures.

1 Introduction

Many forms of analysis and calculations go into the design of a flexible pipeline conveyance system. This design process and ultimately the pipeline products have evolved through time by successive theoretical and empirical advancements. The history of this design and production process has been well documented and has resulted into a succinct, yet mainly empirical, set of design standards. The evolution of these standards has been aided not only by academia, but also by design professionals requiring quality within the pipeline industry. However as the existing conveyance infrastructure ages and a continual push for higher pipeline capacity is made, it has become an opportune time to reevaluate the strengths and weaknesses of these design standards. Understanding the history on the past successes of the existing standards, the authors proposes that there is room for improvement with regard to evaluating conveyance systems as a composite system and not just the various components (e.g., pipeline, joints, linings, pumps, valves, etc) that have been engineered to “play well” together.

To succeed, such a composite assessment should include both static and dynamic evaluations of the pipeline linings, coatings, joints, operating conditions (both normal and abnormal), transient control systems as well as handling and installation issues. This paper identifies some potential areas they may benefit from additional analysis and research. Many of the areas discussed have been researched extensively, but the interrelationships between the components have not. Specifically this paper addresses how and where hydraulic transient pressures are used in steel pipeline design and how and where design professionals can introduce improvement to that component of the design process. Particularly the impacts of transient hydraulic pressures on the internal linings and gasketed joints of flexible pipeline systems. Large diameter steel pipeline and the standards used in its design have been utilized in the core of many of the discussions throughout this paper; however, many of these same issues are also applicable to other flexible pipeline systems.

Throughout pipeline design history, the hydraulic transient pressure condition has been identified as a cause of many pipeline failures. These failures are often quite sudden, resulting in pipeline burst and/or collapse. Through forensic studies, these failures often arise from an isolated incident such as a pump failure or valve closure. Because most of these isolated incidents can be either avoided or mitigated in design and because of the outstanding historical performance and durability of pipeline systems, the industry has become somewhat complacent about transient pressures and their significance in regards to day to day operations. Many pipeline failures are blamed on an isolated hydraulic transient event and/or inadequate hydraulic transient protection when in fact the pipeline itself has either corroded or weakened over time and the normal operating pressure are enough to result in failure.

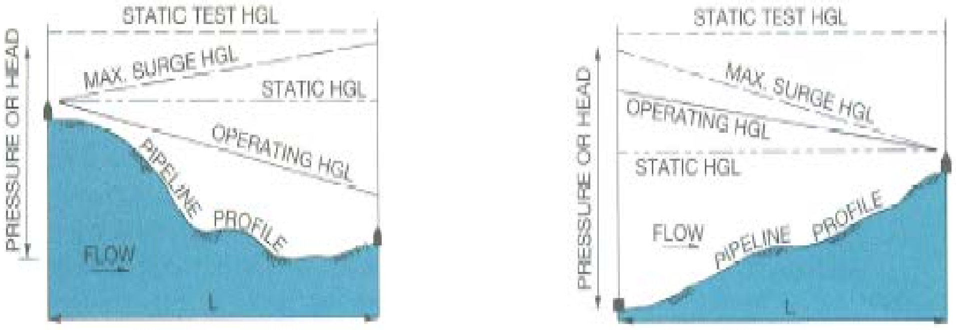
Pipeline designers and manufacturers understand that pipeline systems are dynamic, but current standards, design practices and testing procedures have all been developed around static protocols. As a result, little has been done to understand and improve design standards based on transient hydraulic effects. To establish this point, it is logical to first review the current design approaches and then to introduce a couple of failure modes that are poorly documented and accounted for in general practice.

2 Current Design Approaches

To select an appropriate wall thickness for a steel pipeline, two elements are primarily considered. One is the internal pressure and the other the external pressure. If these two elements are appropriately accounted for, then a pipeline can be designed to be well within the applicable design standards. Although other design considerations may influence the pipeline thickness, including the types of joint and lining systems utilized, these considerations are outside the scope of this work.

2.1 Internal Pressure

Internal pressure originate from the forces the fluid applies to the pipeline wall as a result of molecular collisions. This force arises from the pressure head which is simply computed from the location of the Hydraulic Grade Line (HGL) in relation to the pipeline's position (elevation) along the pipeline profile. In design, once identified, the positive hydraulic transient pressure is assumed as a component of this internal pressure and is subsequently considered a fixed (invariant with time) pressure condition. Other components of internal pressure are the normal and maximum operating pressures, the hydrostatic test pressure and finally the static pressure. If the system is a pumped system, then the pressure generated by a pump at the shut-off head condition should also be considered in design as an internal pressure. Figure 1 shows the internal pressure considerations as defined by M11, the American Water Works Association (AWWA) Manual of Water Supply Practices for Steel Pipe (1). In Figure 1, note the exclusion of the downsurge or negative pressure condition.



Gravity Flow **Pumped Flow**

Figure 1 – AWWA M11 Internal Pressure Design

A pipeline can normally be assumed as a thin walled pressure vessel having a large diameter (bore) relative to the wall thickness. For example, a 48-inch (1200 mm) diameter steel pipeline may have a thickness of 0.25-inch (6.35 mm) which is a D/t ratio of 190:1. Because the pipeline is taken as a thin walled element, in design the pipeline is assumed to have a uniform wall stress.

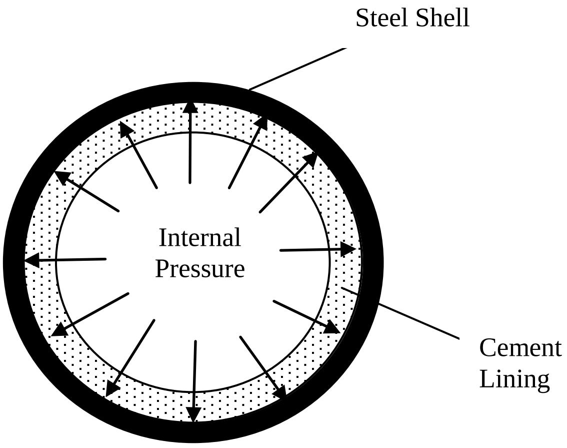


Figure 2 – Internal Loading Free Body Diagram

As a result, the internal pressures are assumed to be acting uniform and radial on the pipeline cylinder. Figure 2 shows the internal loading considered in pipeline design.

The standard design process assumes:

$$S = PD/2t$$

where:

S = Stress
P = Pressure
D = inside Diameter
t = wall thickness

Note that in the standard design, the radial stress (normal) and the longitudinal stress are not considered in the wall thickness design; rather, only the hoop stress is considered. The above simplified hoop stress equation has become entrenched in the pipeline design community and is commonly referred to as the Barlow Formula (2). In most design manuals the variables are manipulated to solve directly for wall thickness (t). Because of its simplicity, inexperienced engineers and designers use this formula to quickly quantify the thickness requirements of the pipeline. What should be understood is that this is where the basic factors of safety and material properties are many times mistakenly assigned. In the AWWA M11 Manual of Water Supply Practices for Steel Pipe[1], hoop stress is assumed to be 50% of the material's minimum yield strength. This would equate to a safety factor against yield of 2.0. As long as the material (steel) does not approach yield the material recovers its original shape and characteristics and therefore the pipeline is deemed safe.

The problem in this formulation is what pressure is considered as the appropriate design pressure. Many design firms assume the worst case condition which may be a static condition in a gravity pipeline, or a pump shut-off pressure condition in a pumped system, or the hydraulic transient pressure condition. Also, because of the cost of the material, many standards use a tolerance greater than 50% of yield to be used for transient events for the worse case condition such as 75% of material minimum yield strength[1]. This provides a 1.5 multiplier against exceeding the material yield stress. It is interesting that no design standard considers ultimate tensile strength of the material; however, the American Society of Civil Engineers (ASCE) Steel Penstock Manual (3) allows an emergency load stress of 90% of the tensile strength. It should also be noted that this design is for the steel thickness only and that the lining, coatings and joints components are note considered it this analysis.

It can be argued that this design for internal pressure is highly conservative for tensile stresses in a pipeline system. Later, an argument is made that, for normal operating pressures in a water system, this design approach rarely controls and the pipeline is even made thicker for handling and in many cases for corrosion allowance. This naturally provokes a critically important question: why do we have tensile failures? To set the stage, we need to consider external pressure.

2.2 External Pressure

External pressure(s) arise from over-bearing loads such as the weight of the soil on a buried pipeline, the weight of equipment or trucks above the pipeline, the hydrostatic pore pressure of the groundwater on the pipeline wall, and last but not least the internal pressure below atmosphere pressure (partial or full vacuum pressure) that may be present. Since atmospheric pressure forces are normally ignored, this last external pressure condition actually originates as an internal pressure; in design, it is coupled with the external pressure calculation because of the direction of its forces on the pipeline wall. As was the case for internal pressures, external pressure are treated as fixed values in design. This means the dynamic loading condition in not factored into the design for internal or external pressure conditions.

In design, the external pressure is the accumulative load applied to the pipeline as a result of four loading conditions: 1) the hydrostatic load, 2) the earth load, 3) the live load, and 4) the internal vacuum load. The external pressures introduce a compressive force on the pipeline and in design this load is assumed uniform and radial. Also, the pipeline is usually assumed empty requiring the pipeline to resist all the external forces with no benefit from the internal pressures. The design approach is to sum up all the characteristics of the over-bearing load and to evaluate the summed equivalent pressure due to the influence on deflection and the collapse pressure of the pipeline design. Pipeline deflection is the “magic” or index parameter that is best understood by design professional when discussing the flexible pipeline design relative to external loadings. Many pipeline design specialist assign an allowable deflection relative to the type of pipeline lining and coating (4) and joint systems. That is, for more rigid (relatively inflexible) lining and coating systems (e.g., mortar lining, mortar coating) less deflection is tolerated. In the pipeline design process, deflection is the one parameter that even considers the pipeline design as a system rather than as individual components simply because of its consideration in lining, coating and joint selection, but the loading is still taken as static. Figure 3 shows the external loading considered in pipeline design.

A significant amount of analysis and research work has been performed on flexible pipeline design over the last 50+ years (AWWA Manual M11, AISI manuals on Welded Steel Water Pipe, and ASCE Buried Steel Penstock Manual, 3). During this period, professor Reynold Watkins of Utah State University has been a key player in the development and understanding of external loading on the pipeline shell (5, 6) and the influence of soil mechanics in the design of flexible pipeline. Professor Watkins is well known for his statement “It’s the soil stupid”. And of course, for buried pipeline there is a known and practically understood benefit to having good embedment and soil material around your pipeline to help offset or redirect the over-bearing loads of external pressures.

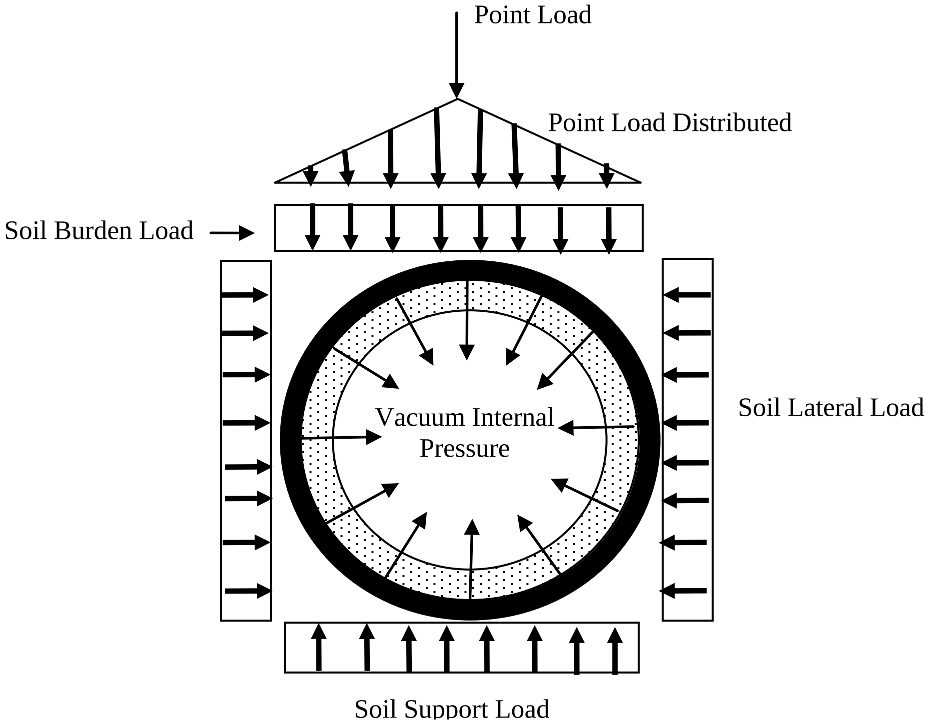


Figure 3 - External Pressure Free Body Diagram

The structural failure of a pipeline due to external loads may be from either collapse or buckling. There are various equations that are used to estimate the collapse pressure. The AWWA M11 design approach (1) assumes Timoshenko's formula (7) to quantify the collapse pressure of the pipeline and Stewart's formula for buckling. In the AWWA approach for collapse, the Timoshenko's formula is based solely on pipe mechanics, and assumes a uniform, radial load of the external pressure and a perfect and infinitely long cylindrical tube. As a result, this equation does not account for inconsistencies in the pipeline wall or material or shape and therefore may greatly misrepresent the actual collapse pressure of the pipeline. As noted by AWWA M11 Guide (1), there has been many attempts to develop an empirical formula to estimate the relevance of these inconsistencies/imperfections in the pipeline, but none have been adopted by the standard design guidelines.

It should also be noted that the dynamic behavior of the over-bearing loads (external loads) albeit a truck's live load or a hydraulic transient condition are not considered. The American Association of State of Highway Transportation Officials (ASHTO) and the American Society of Mechanical Engineers (ASME) have developed some impact factors for dynamic live loads (8), but no impact factors have been considered for hydraulic transient pressures conditions.

2.3 Miscellaneous, but Important Design Considerations

In a flexible pipeline design, especially at larger diameters, the stability of the ring stiffness provides great advantages to the pipeline during its transport and installation. Before the pipeline is backfilled and the stability of the embedding material can be added to support the pipeline, the maximum allowable deflection must be handled by the thin steel shell itself. This component of the thickness design is significant because the required ring stiffness alone may exceed the required thickness of the pipeline for internal or external pressure designs. Also, pipelines with mortar lining and coatings, benefit from the lining and coating's added rigidity, but the allowable deflection is greatly decreased if cement mortar lining and/or coatings are used. So this can be seen as a "Catch-22" or a double bind. The equation used for the minimum thickness in steel pipeline design for handling has been empirically developed over time and is given a great deal of attention because transportation is generally seen as the riskiest part of the installation and also any damage to the pipeline (wall, lining, coating, etc.) can be easily observed. It should be noted that the AWWA M11 recommendation for this minimum handling pressure was developed by J. Parmakian in 1982 also known for his publication "Waterhammer Analysis" outlining the use of the graphical method in transient analysis.

3 Transient Pressure and Wall Thickness Design

As discussed above, in pipeline system design, transient pressure conditions are simply considered as fixed pressures that are included in the analysis of the pipeline with respect to pipeline's yield strength and collapse/buckling pressure. Currently the transient or dynamic nature of the pressure fluctuation is not accounted for in design. So is the current design approach appropriate? If not, what changes should be made to benefit future design?

There are two evident areas in which the dynamic pressure condition should be considered. The first is at the joint, especially at gasketed (push-on) joint connections. The second is in the lining. The remainder of this paper discusses the potential use of transient pressure analysis with regard to the joint and lining designs. Special attention is paid to cement mortar lining, which is a commonly used lining system on both steel and ductile iron pipelines in the potable water industry.

3.1 Joint Design

There are various mechanical systems that make up the available joints in a steel pipeline. Because steel can be welded at reasonable temperatures, many designers and owners require a welded joint. The welded joint, if made properly, is excellent from a structural integrity perspective; however, it is also expensive. Not only is the joint costly to manufacturer, to properly weld a pipeline, a significant delay in construction is required and time is money.

The joint with the least initial capital and installation cost is the simple gasketed push on joint. These joint types are typically used in smaller diameter pipelines and at pressure below 250 psig (1700 KPa)[9]. However, because of the cost of the welded joint, many owners have asked for better justification for why a push-on joint should not be used. The qualitative answer is that a push-on joint is not viable for high pressures and larger diameter pipeline systems. From our discussion earlier about the design standards and what standard design parameter effects joint design, it is clear that the pipeline deflection is the only design parameter. So, under a given external load, the deflection is limited so that the gasket does not unseat from the joint. The pipeline manufacturers (Northwest Pipe Company, American Cast Iron Pipe Company) have tested their gasketed joint systems under various loads and deflections and have been able to document the joint's performance. Again these test have been static test and have been performed under controlled and relative uniform deflection scenarios. In mechanical system a flanged joint with a gasket is commonly used. The potential failure mode of the gasketed joint, albeit a push-on or a flanged joint, is the gaskets extrusion through the joint due to high pressure or the disbonding or separation of the gasket from the joint due to excessive deflection. Exhibit 1 in Figure 4 shows an extruded gasket in a flanged joint that had been subjected to repeated high transient pressures in excess of the flange pressure rating. Exhibit 2 shows a failed gasketed joint which resulted in significant pipeline erosion and ultimately pipeline failure.

Exhibit 1: extruded gasket **Exhibit 2: failed gasketed joint**

Figure 4 – Examples of pipe joint failures

As we strive to procure progressively lower cost designs, we are asking questions that were previously avoided because of the perceived risk. However, as technology improves, we as engineers are becoming more inclined to challenge safety factors and the perception of risk. Therefore, designers and engineers are asking what are the limitations of the gasketed joint. In short, designer are saying, don’t tell me when and where push-on gasketed joints performs well, but tell me when and where they will fail. The authors challenge that the pipeline community does not have the test, data, nor the experience to answer this question.

The gasketed joint is another double bind, because the cost savings that are realized from the use of a less expensive joint system many times are used in manufacturing a thicker pipeline shell. The thicker shell is required to maintain the integrity of the pipeline system as a whole by allowing a smaller deflection under the imposed external loads. Because of a dependence and identification of deflection as the key parameter for assessing joint performance, designers seek to reduce deflection to ensure a system’s integrity. The deflection may simply be one mode of failure for a gasketed joint. Another may be the dynamic loading and its effect on the elasticity of the gasket and the ability of the gasket to deform dynamically with the imposed transient load. With this in mind, a stiff gasket, that may be suitable for higher internal pressure, may fail due to its inflexibility when a downsurge or negative pressure transient wave is propagated through the joint. The density/stiffness of the material may prevent the gasket from deforming rapidly enough to prevent the gasket from being carried into the pipeline. And, of course, the counter argument can be made. If the gasket is made pliable enough to handle the downsurge or negative differential pressure change then the gasket may extrude through the joint. This is a topic remaining to be analyzed and a question left to be answered by the pipeline design professional community.

3.2 Lining System Design

Linings have been used for many years either to separate the steel shell from the fluid conveyed or to weaken the corrosive potential of the fluid. The primary purpose of a lining system in a steel pipeline is to reduce the potential for corrosion.

Although there are various kinds of linings used, there are two main types. The first type utilizes Polyurethane. The Polyurethane material is heated and then sprayed on to the pipeline wall very similar to a painting process. The bond of the Polyurethane lining to the pipeline wall is through adhesion. Because of how the Polyurethane lining is installed (generally sprayed on) there is a potential to develop “painter holidays” that expose the steel to the product fluid and thus introducing a corrosion cell. These gaps may also become a point in which the pressurized fluid can seep behind the lining and potentially disbond the lining from the pipeline wall during a change in pressure or transient pressure event.

The second lining type, which is much more common in the raw and potable water industry, is the cement mortar lining. This lining system consists of a dense homogenous cement and sand mixture that is centrifugally cast onto the pipeline wall by the manufacturer. In this centrifugal application process, the lining is not adhesively bonded to the pipe wall so once the cement has dried and set, the lining is simply held in place by the radial stresses in the lining. Additional stresses occur in the lining during the transport of the pipeline due to the allowed ring deflection of the pipeline. These stresses due to ring deflection will generate small cracks in the lining system. Also, because the cement mortar lining is a porous material, it is proposed that the conductive property of the lining will allow a differential pressure to be set up across the lining thickness during a hydraulic transient event. Currently, transient pressure is not considered in the design of the lining system. Actually, there is little consideration, other than the lining’s influence of ring stiffness, of the lining in the pipeline system design process.

4 Analysis of Cement Mortar Lining

The remainder of the paper focuses on cement mortor lining and particularly the influence of transient pressure on the lining. A proposed analysis is developed to assess the failure potential of the cement mortar lining due to the dynamic loading from a hydraulic transient condition.

The current design process only considers the static loading on the pipeline. Even though the extreme static loading procedure may be adequate for the thin steel shell design, the authors propose that the process is not adequate when considering a porous lining material (cement) that is weak in tensile strength. To properly analyze the dynamic loading on the cement mortar lining, two elements need to be closely considered. The first is the loading itself. How does the differential pressure setup across the lining during a hydraulic transient event? The second is the analysis of the stress incurred by the loading and how it compares to the lining’s material strength.

4.1 Assumptions

This analysis, as proposed, requires several general assumption to allow the problem to be simplified and numerical formulated.

1. It is assumed that the cement mortar lining has no adhesion to the pipeline wall, and therefore, the mortar and steel are two separate bodies not acting on one another. When the pipeline is operating normally, the internal pressure will stress the pipeline wall and slightly expand the steel. The cement mortar lining, which was centrifugally cast on to the pipeline wall, will also be positively stressed from this expansion. However, this analysis assumes that the additional stress resulting form the expansion of the steel is not present. Therefore when the dynamic load is applied, the relaxation of the steel and the cement lining is not considered. Also the shear stress at the steel/lining interface will not be realized. When combined with the shear stress in the lining, this unconsidered shear stress at the pipeline wall may have significant strengthening effect on the lining. Even though the adhesive property of the centrifugal casting is not high, it is proposed that this parameter along with the normal operating stress imposed should be evaluated for sensitivity.
2. A failure is considered as a stress greater than the ultimate tensile strength of the mortar itself. So the dynamic load (normal to the pipe wall and mortar) would need to overcome the circumferential stresses and ultimate shear strength of the mortar. Only the hoop stress is considered; the longitudinal stress and the radial stress are not considered.
3. The cement mortar lining is initially fully saturated and therefore the initial pore pressure throughout the lining is assumed to be the same.
4. The cement mortar lining is homogenous with fixed conductivity through its entire cross section.
5. The dynamic load is uniform and radial.

The first requirement in this analysis is to develop a loading rate across the porous lining material. This loading rate helps define the magnitude and duration of the imposed differential pressure. With this differential pressure defined, an analysis of the stress, strain and potential failure of the lining can then be made.

4.2 Hydraulic Transient Loading Analysis

If the cement mortar lining is homogenous and 100% saturated and free of air voids, then a common assumption in soil mechanics is the celerity (sonic wave speed) through the lining would be equal to the fluid sonic wave speed. However, this also assumes that the fluid is incompressible and the boundary layers are rigid. These two later assumptions would result in a instantaneous pressure change across the lining and therefore, the dynamic nature of the loading would become static. The authors propose that these later assumptions are invalid with regards to the lining.

Because of the porous nature of the cement mortar lining, many hydraulic analyses, similar to the analysis considered here, can be found in soil mechanics. In soil mechanics there is a classic one dimensional theory describing the dynamic behavior of hydraulic loading to the corresponding change in volume for a completely saturated compressible soil. This theory, introduced by Karl Terzaghi in the early 1920's, is now known as the Terzaghi One Dimensional Theory of Consolidation (10). The authors propose that, through a similar approach to Terzaghi’s, a succinct and viable numerical method can be developed to assess the dynamic loading and differential pressure across the cement mortar lining during a hydraulic transient event.

4.3 Stress, Strain and Failure Analysis

A statically loading free body diagram was shown in the discussion of both the internal (Figure 2) and external (Figure 3) pressure design. In the static loading free body diagram shown above in the internal and external pressure design discussion, the uniform radial load is broken down into hoop stress (x), longitudinal stress (y) and radial stress (z). Through basic pipe mechanics, the hoop stress in the x direction is found to be approximately 10 times that of the longitudinal stress and approximately 48 times those in the radial stress (which is equivalent to the internal/external pressure). Therefore, the largest stresses are felt along the pipeline wall from the hoop stress, which at a point is perpendicular to the load. In the design analysis of the steel shell thickness the stresses are assumed uniform over the thickness of the steel shell. This is an adequate assumption because the diameter to thickness ratio is very high >100:1 and therefore a thin shell is an appropriate assumption.

In a porous material under a static loading condition, a similar analysis can be performed and similar stresses will be found. However, when a dynamic load is introduced to the internal wall of the cement lining, the pressure and stress on the top side of the cement lining will for a time maintain the initial pressure (Po) pressure condition while the internal face of the lining will be subjected to a lower transient pressure (P_1). Because of the hydraulic conductive property, assumed similar to the Terzaghi's One Dimensional Theory of Conolidation of the porous material (10), a pressure differential will develop due to the flow resistance across the media.

Figure 5 shows a free body diagram of the applied pressures on each face of the lining. The magnitude of this pressure differential will generate a hoop stress differential between the top and bottom of the lining. This stress differential can then be compared to the ultimate strength in shear of the lining and predict if failure is likely.

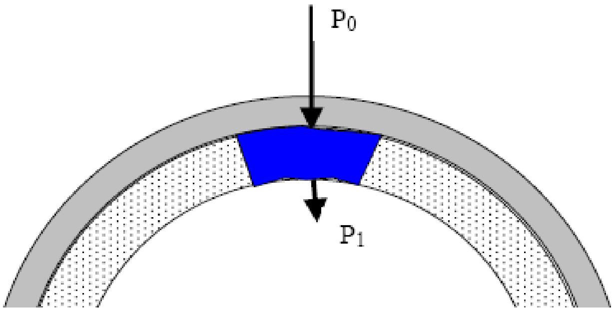


Figure 5 - Free Body Diagram of dynamic loading

5 Conclusions

Although structural considerations are crucial to the success of any pipeline system, there as been a strong tendency to treat transient loadings superficially and simplistically during pipeline design. The unwarranted simplifications can arise when the range of loadings are being considered, or when their duration and transient nature is neglected, or when the behaviour of the lining is being considered. One mode of failure that is particularly worrisome and almost wholely neglected is associated with the possible influence of transient loadings on cement motor linings.

This analysis of cement motor linings when subject to transient events comes down to how much differential uniform radial load introduced by a negative transient pressure wave can the cement mortar lining resist without failing. The only resistant force holding the lining together is the circumferential compressive load. Due to the history of cement mortar lining and steel pipeline systems as a whole, the authors believe that the stresses incurred from the sub-atmospheric dynamic loading of the cement mortar lining will not introduce a failure concern. However, this research may allow for refinements in the thickness requirements of the lining that is applied and therefore potentially save cost on the pipeline system. If this dynamic loading of joints and linings does show a potential for failure through the numerical analysis, the authors propose that the pipeline manufacturers be solicited for physical testing to evaluate the potential for lining failure.

When considering the dynamic behavior of an elastic/flexible or rigid/inflexible material a dynamic loading is required to properly assess the deformation and ultimate strength/strain that the material has. In hydraulic transient analysis, there has been a significant history of empirical analysis and testing of mechanical equipment so that the analyst can better define the dynamic characteristics of the pipeline system. However, the authors propose that the inclusion of the dynamic behavior of the joints and lining systems and a closer assessment of sub-atmospheric pressure conditions may provide the pipeline design community a more refined and possibly a justifiably less expensive product through an equally robust design process.

Because cement mortar lining is used in both Steel and Ductile Iron pipelines to reduce the corrosion potential of water, if this failure mode proves to be significant, then the need for more proactive or primary surge control will be required in conveyance systems not only to protect against catastrophic failures but also to provide a comprehensive corrosion control on the pipeline by allowing the lining systems to maintain its integrity. This may also influence the design professional on the type of hydraulic transient control devices that may be used.

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