Introduction

The speed at which pressure waves travel along a pipeline system is commonly referred to as the pipeline ‘wavespeed’ or ‘celerity’. It can typically vary between 400 m/s and 1100 m/s under steady state conditions depending upon the pipe material (a low wavespeed would be expected in rubber hoses or GRP pipelines whereas the higher wavespeed is often seen in Steel pipelines). The main cause of the differences in wavespeed is the Young’s Modulus of the pipe wall. Steel is a very rigid pipe whereas rubber and GRP will distend more readily as the pressures in the pipeline vary.

The vast majority of commercially available software packages use a fixed wavespeed approach to transient modelling whereby a wavespeed is input into the model for every pipe and this wavespeed will be used at every distance increment and time step for that particular pipe. Certain programs claim to use a variable wavespeed approach to modelling but, in reality, this just refers to the fact that a different wavespeed can be used at the start of the simulation but the wavespeed remains constant throughout the simulation.

Surge Pressures

The pressure rise which is caused by a transient upset event in a pipeline system (such as pump or valve operations) is determined by the Joukowski equation:

$$\Delta h = \frac{c.\Delta v}{g}$$

Δh	Pressure change in m
c	Wavespeed in m/s
Δv	Velocity change m/s
g	Gravity

Wavespeed

One of the key components in the Joukowski equation is the pipeline wavespeed (designated ‘c’ in the above equation):

$$C = \frac{1}{\sqrt{\frac{We(1-\varepsilon)}{g}\left(\frac{1}{K}+\frac{\varepsilon}{p}+\frac{d}{tE}\right)}}$$

Effective Density — Liquid Compressibility — Pipe Distension — Free Bubble Content

C	**Wavespeed**
We	**Fluid specific weight**
g	**Gravitational constant**
ε	**Fraction of free gas**
K	**Fluid bulk modulus**
p	**Local pressure**
d	**Pipe diameter**
t	**Pipe wall thickness**
E	**Pipe wall Young’s Modulus**

The transient software program which has been used by Hydraulic Analysis Limited over the past 40 years (VariSim) uses a true variable wavespeed. The software recalculates the wavespeed at every location in the pipeline during every time step during transient conditions and also includes for changes in the volume of entrained air or gas in solution as the pipeline pressures vary. It is only by adopting this approach that truly realistic modelling in terms of peak pressures, pipe loads and timing of events may be achieved.

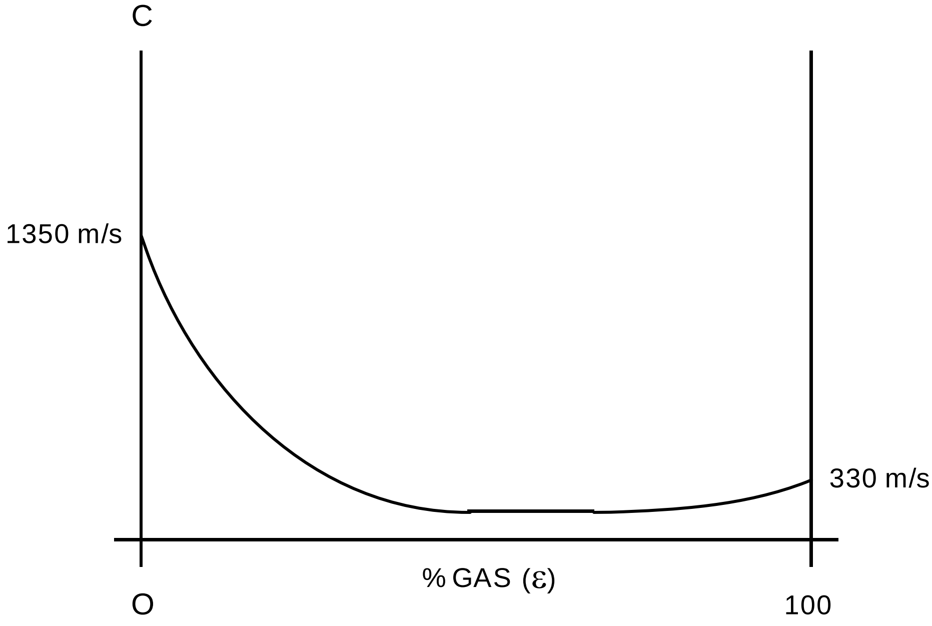
The main reason for the high accuracy levels which are obtained in VariSim is the fact that it accounts for the effects of local pressure changes on the pipeline wavespeed. It can be seen from the equation on the previous page that the wavespeed can by separated into four distinct separate areas:

1. Liquid Compressibility – used to determine the basic elements of the wavespeed calculation throughout the pipeline based upon the Bulk Modulus of the fluid. This component generally has limited effect on changes in the wavespeed as pressure transients are transmitted through the pipeline. It can however be modelled as a variable if the fluid Bulk Modulus is likely to be significantly affected by pressure / temperature changes along the pipeline. Obviously the Bulk Modulus will vary considerably between different fluids.

2. Pipe Distension – this component again mainly impacts on the basic elements of the wavespeeds calculation throughout the pipeline based upon the distensibility of the pipe. The physical pipe components are used in this part of the calculation (diameter, wall thickness and Young's Modulus). This component has no effect on the changes in wavespeed as pressure transients are transmitted through the pipeline as the input parameters are all physical constants, but can vary considerably in systems with different pipe wall materials and pipe dimensions.

3. Free Bubble Content – this is the most critical aspect of any transient modelling if accurate results are required. The two components of this part of the wavespeed equation (local pressure at every distance increment along the pipeline and the volume of free air or gas derived from the dissolved and entrained gas in solution at STP) will vary as the pressures waves are transmitted though the pipeline. As the pressures vary, the percentage of air or gas dissolved in solution (by volume) will also vary. Hydraulic Analysis Limited uses past

experience, from over 6,000 projects, to select the most suitable value for the volume of entrained gas at STP. This component is particularly critical to modelling low pressure events as the gas volume will expand with falling pressures and this can often prevent vapour pressures from occurring in the model (when combined with gas being drawn out of solution as the fluid bubble point is reached). When comparing fixed wavespeed modelling to site measurements, there is a greater tendency to reach vapour pressures in the model which are not achieved in reality. The following graph gives an indication of how critical the free gas content is in determining the pipeline wavespeed:



4. Effective Density – this component of the wavespeed equation is significant to obtain high levels of accuracy during transient upset conditions as the free air or gas content entrained in solution is again included.

Pipe Loads

The variable wavespeed modelling approach used by Hydraulic Analysis Limited ensures that the formation and collapse of vapour pockets and the rates of pressure change are accurately modelled. These two features are essential for accurate prediction of the pipe forces which occur in a system.

Pipe loads are caused by pressure changes (and to a lesser extent velocity changes) and hence the rate at which a pressure wave travels along a pipeline is a significant factor which affects the pipe loads in any given pipe section. Hydraulic Analysis Limited recognise that fixed wavespeed modelling will generally produce overly conservative results in terms of peak pressures and hence inherently allows for a built in 'safety margin' but this is not the case for pipe loads which are often significantly underestimated by using fixed wavespeed modelling. Pipe loads are affected by the pressure differential across a pipe which is dependent upon the rate at which a pressure wave passes through the system. In certain scenarios, a drop in wavespeed will result in a pressure wave travelling slowly through the system and hence allows for a greater pressure differential to build which results in higher pipe forces. By modelling a high fixed wavespeed, this can often be neglected in the design study.

A good example of a system which was under-designed due to the use of a fixed wavespeed model comes from an LNG loading system. The peak pressure generated by the collapse of a vapour pocket downstream of a closing valve was identified by the original design study (before HAL's involvement), but the scenario was simply accepted, as the peak pressure remained within the pipeline design pressure. In fact the LNG loading pipeline broke its concrete anchors and moved the pipework more than a metre, leaving both jetty expansion loops in need of replacement.

Case Study

Whilst the above information discusses the differences between fixed and variable wavespeed modelling, it is best demonstrated in a case study. The following two graphs have been taken from a transfer pipeline which HAL were asked to investigate following commissioning. The original hydraulic design had been based upon fixed wavespeed modelling and when the client recorded the actual transient response of the system using high speed data acquisition software (running at 20 Hz), it was clear that the on site response differed significantly from the expected results in the original surge analysis study. It was noticed that both the timing of the surge response and also the magnitude of the pressures were very different.

Subsequent to the site measurements, HAL were asked to model the system independently and the results showed that the expansion of the volume of dissolved air in the fluid during low pressure events was having a significant effect on the wavespeed of the fluid and hence the surge response of the system. By assuming a fixed wavespeed, the original modelling work did not account for the fact that wavespeed (and hence surge pressures) vary with local pressure and also the volume of dissolved air in the fluid. VariSim recalculates the wavespeed at every location in the pipeline for every time step during transient conditions and includes for changes in the volume of dissolved gas or air as the pipeline pressure varies. It is only by adopting this approach that truly realistic modelling in terms of peak pressures, pipe loads and timing of events can be achieved. Subsequent comparison of the HAL model results with the site results showed a difference of just 3% and the unexplained pressure spikes in the fixed wavespeed model at simulation times of 16s and 104s were eliminated.

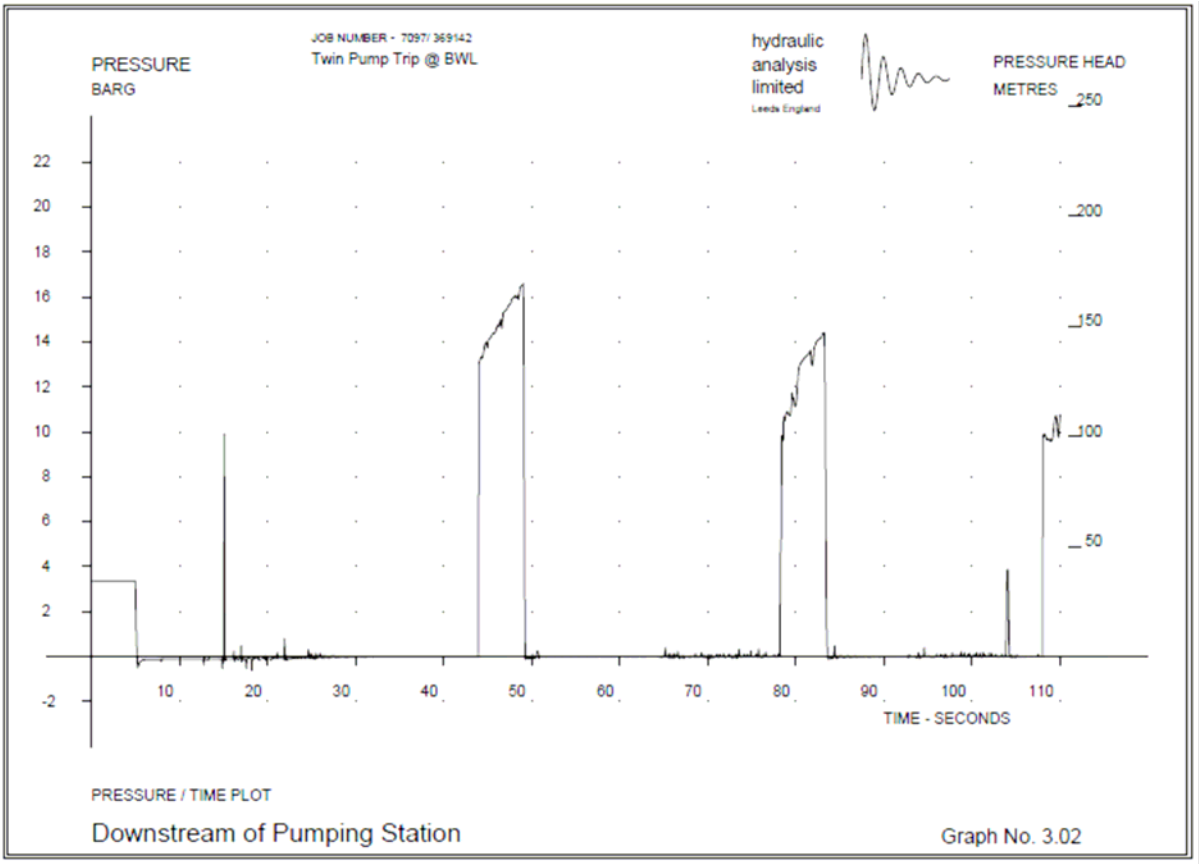


Figure 1.01 – Fixed Wavespeed Model (wavespeed fixed at 900 m/s)

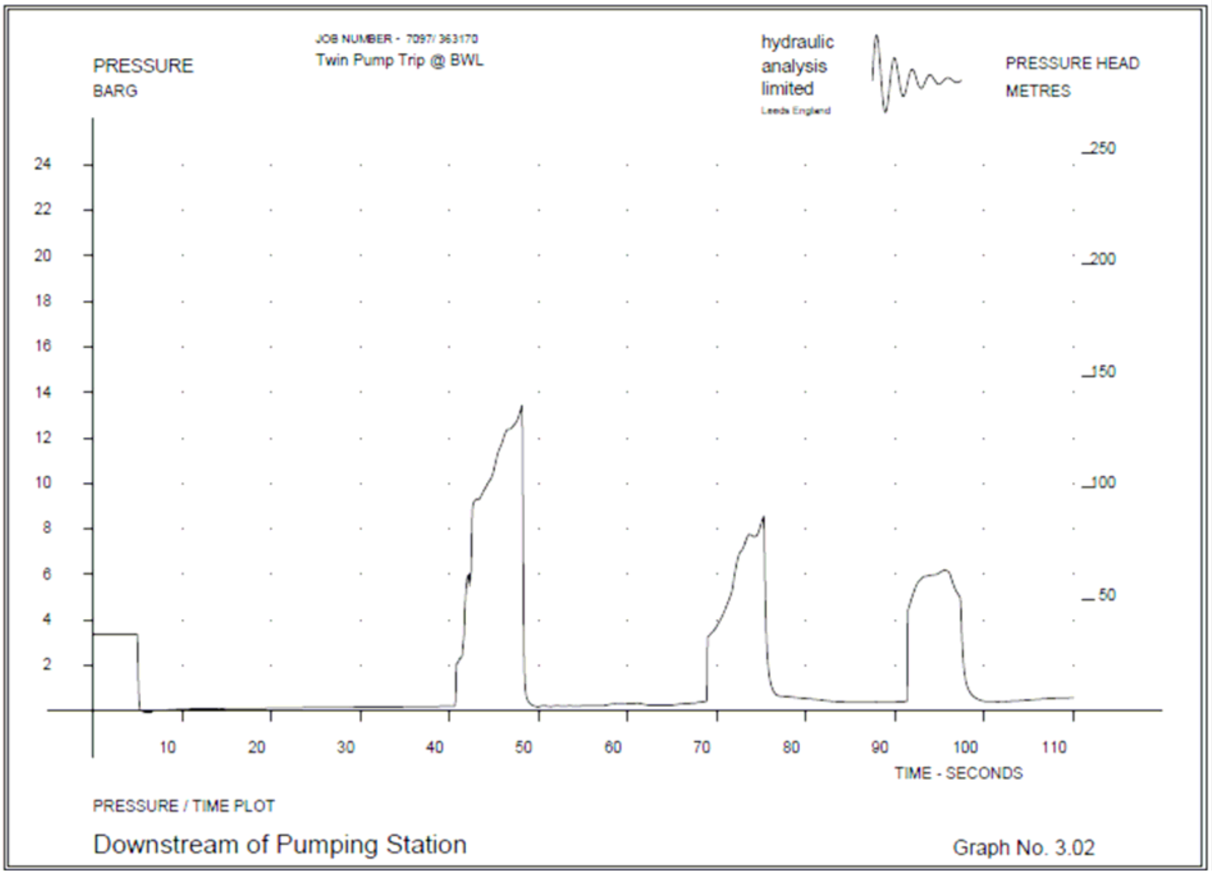


Figure 1.02 – Variable Wavespeed Model (volume of entrained air fixed at 0.05% at STP)

One of the more interesting aspects of this modelling work demonstrated the effect that varying the dissolved air content of the liquid had on the surge response of the system (doubling or halving the free air content resulted in a significantly different surge response due to the effects of vapour formation in the system). This project demonstrated that, even if an engineer is using a powerful software tool, they will still need to rely heavily on accurate input data and past experience which are core strengths of Hydraulic Analysis Limited.

Vapour Handling

VariSim has been validated during the past 40 years on over 6,000 projects and accounts for vapour pockets expanding along the system as the pressures fall. The model will also correctly consider whether there are many individual vapour pockets forming or one or two large pockets. The model also accounts for the vapour pocket reducing in size as the pressures in the system recover until the pocket collapses at which point there is a sudden pressure change as the two liquid interfaces either side of the vapour space meet. It is this change in velocity which generates the surge pressure rise when the vapour pocket collapses. Pipe forces occur due to pressure changes, not necessarily high or low pressures i.e. a system can experience a 20 bar pressure rise but if it occurs over several seconds then the pipe forces will be low. Contrary to this, a 6 bar pressure rise can generate very high pipe forces if it occurs over a short time period (in some cases this could occur in less than 0.1 seconds).

It cannot be assumed that the only occasions where variable wavespeed modelling is advantageous over fixed wavespeed modelling is where vapour pocket formation and collapse occurs. This is not always the case as the closure of a valve can generate very different pressures (and pipe loads) when comparing variable and fixed wavespeed modelling. This relates to the point at which a closing valve starts to bite into the flow. The initial pressure rise can generate a shallow fronted pressure wave whereas the latter stages of the valve closure can result in a steep fronted wave which can catch and overtake the initial pressure wave. This results in a single steep fronted pressure wave passing along the system which can generate very high pipe forces, especially when closing a gate, ball or butterfly valve.

Conclusions

Wavespeed varies with a number of factors, including local pressure, and hence it cannot be considered as constant if high accuracy levels are required. In fact, the wavespeed can vary significantly during transient conditions (from 100 m/s to 1200 m/s in some events - such as pump trip or rapid valve closure). As a result of this, the difference in pressure experienced along a section of pipework, and the timing of events will vary in a way fixed wavespeed modelling simply cannot capture. All simulations carried out by Hydraulic Analysis Limited include the effects of variable wavespeed and, as a result, a very high accuracy level is achieved for most flow conditions and upset events. This allows the accurate and reliable calculation not only of peak pressures, but pipe loads, trip settings, controller constants and many other useful factors. Whilst using fixed wavespeed is simpler and quicker, accuracy is often compromised with this approach.

The software package used by Hydraulic Analysis Limited (VariSim) always defaults to using variable wavespeed for the fluid. It follows that, if the wavespeed varies in real life, then the wavespeed should vary within the simulator. This is especially true if trying to match real life conditions. It is also a common misconception to assume that a fixed maximum wavespeed will result in the highest possible surge pressures. Although this may well be the case in the majority of situations, fixing the wavespeed will lead to the timing of critical events being incorrect. It may also lead to the highest surge pressures being generated in the wrong section of the system.