ABSTRACT

LNG Terminals represent key infrastructure for gas markets in many regions. With markets shifting to a more global approach, what happens when your operational cases evolve, and the original design specifications are challenged? Or worse an operational event exposes weakness in the design?

The priorities on any site continue to be around safe, profitable operation and maximising capacity/uptime. Under normal operation piping systems can withstand the resulting stresses. Events such as rapid PERC closures, Emergency Shut Downs (ESDs), valve operations, and pump trips can all create transient effects. Consequences can include excessive surge pressures which in turn lead to increased pipe stresses and structural loads.

An ongoing relationship with a large LNG terminal operator has driven studies into hydraulic surge in pipelines following Emergency Shut Down (ESD) events and developed this hydraulic understanding to include bend forces and resolved pipe forces which could be passed into targeted structural analysis. Over time, scenarios have become more complex including for example an increasing need to be able to re-load ships from a site originally designed as an import terminal. Alongside the technical challenge of these studies; a key factor was generating justifiable rationalisation of all permutations of operating scenarios into a manageable quantity of worst-case simulations for a multi-tank and multi-jetty site.

Combined with the increasing complexity of cases we were required to develop methods to run simultaneous simulations and manage the model files and outputs in a reliable fashion. More recent work has led to feeding the force outputs into static and dynamic load analysis to understand the force and harmonic interactions with the physical structures on the site. Pressure and force results were extracted for each scenario using a high-fidelity hydraulic model and then utilized in structural analysis tools for further analysis.

This paper outlines the evolution of a complex modelling problem, and the effects of working on an inherited model from a 3rd party and architecture built on scripting tools to solve problems now integrated into our modelling solution. With the concept of simultaneous modelling runs and parametric studies commonplace in today’s environments, we consider the progression of this approach to meet future requirements.

The Problem

The operator of a large LNG site approached DNV GL asking for hydraulic modelling of surge under ESDs. The site in question had a ship jetty feeding tanks 4km inshore. Now the site has expanded with further cryogenic lines and tank phases equating to over 600 pipes and bends to consider. Over this time the commercial operation of the site has also moved from a purely import terminal to meeting the changing demands of the LNG shipping industry. As such analysis has been required at various stages of this evolving terminal operation.

Initial work involved analysis of the effects of a sudden PERC valve closure. PERC valves (or Quick-Connect-Disconnect-Coupling – QCDC) are designed to rapidly shut and implement a safe break-away from the ship in the event of an emergency, the consequences of which can be quite severe pressure effects and reaction forces. Detection of a PERC closure then triggers the site ESD to shut-in the resulting pressure waves to limit the propagation of this through the system.

Key interests for these studies were to ensure the system remains within safe operational limits under these fast-transient conditions.

This site layout and complexity presents a multifaceted modelling problem, with consideration of LNG column collapse, coupled with many operational permutations; challenging both modelling expertise and computational power when the project first began in 2008.

Basics of Surge

Discussion around hydraulic modelling begins with the basis of
a steady-state pipeline. This steady-state implies some key conditions: the mass of fluid entering the system must equal the mass leaving the system; equally the total energy possessed by a unit of mass entering the system must equal that of a unit of mass leaving the system. 

One description of a steady state system might be derived from Euler’s Equation: [1]

\[ \frac{dp}{\rho g} + \frac{u\,du}{g} + \frac{2f\,u^2}{dg}\,dL = 0 \]

\[ \text{Elevation} + \text{Pressure} + \text{Kinetic Energy} + \text{Friction} \]

(Note the Darcy-Weisbach substitution in the Friction term)

<table>
<thead>
<tr>
<th>x</th>
<th>Elevation</th>
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<tbody>
<tr>
<td>p</td>
<td>Pressure</td>
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<tr>
<td>( \rho )</td>
<td>Fluid density</td>
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<tr>
<td>( g )</td>
<td>Gravitational constant</td>
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<tr>
<td>u</td>
<td>Fluid velocity</td>
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<tr>
<td>f</td>
<td>Frictional coefficient</td>
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<tr>
<td>L</td>
<td>Length (pipe axial)</td>
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With no appreciable elevation change, nor kinetic energy change in steady state, the following simplification can be made:

\[ \frac{dp}{\rho g} + \frac{2f\,u^2}{dg}\,dL = 0 \]

However, steady state behaviours (especially in simple systems) can almost be calculated by hand and negate the need for a complex hydraulic simulator. Transient simulation modelling refers to time-varying analysis, with interest in the change in conditions over time. These simulations might be describing a start up or shut down of a line. The conditions stipulated earlier for mass and energy remaining constant in the system are now not met and the approach for describing a system becomes more complex. Physical principles still apply such as conservation of mass, momentum and energy; these key points allow a system to remain constant in the system are now not met and the change in conditions over time.

The assumptions and parameters used within the modelling can have key impacts on the behaviour of the system, especially under surge. Choices for items such as reference conditions (Pressure, Temperature, etc.), equation of state (EoS), thermal mode and fluid properties. The model extension involved highly detailed replication of the LNG site, working through each pipeline isometric drawing to establish bend & device locations, diameter changes and elevation profiles across the model. Valve travel times and closure curves were also inputted for the given specifications at each location. The LNG fluid assumptions were also adjusted based on a data sample from shipment deemed representative of “normal”.

The initial scenario work quickly showed the site behaviour was particularly sensitive to column-collapse. This is the system exhibiting behaviour where the fluid, initially in a single liquid-phase, creates a vacuum gaseous-phase due to momentum in the fluid pulling against slowing fluid, which then rapidly contracts as the phase returns to liquid. A simple example of this is the fluid downstream of a closing valve. The liquid has momentum moving away from the valve, but the available fluid at the valve is reducing, causing a drop in pressure (and density) as this momentum is reducing. In extreme cases the fluid cannot accommodate the reduction in pressure, dropping below the vapour pressure of the fluid and becoming gaseous. This vapour state is not sustained and rapidly returns to a fluid state as the fluid momentum in the pipe balances, which in turn causes a large localised pressure spike due to the return to liquid state. See Figure 1.

A key feature of Surge analysis is then the progression of this pressure spike around the system being modelled. In the case of plants such as LNG terminals ESD valves are used to compartmentalise the system, preventing progression of the pressure wave across the wider site. In modelling terms hydraulic calculations are taken at intermediate positions along pipes – deemed knots, knot spacing determines the ability of the model to track severe transients (surge) along the pipeline. A smaller knot spacing (more knots per pipe length) increases modelling transient tracking, however this has a knock-on
The Need for Forces

The basis for the initial analysis of this site was understanding the pressure transients on the site. After these first analyses the client was keen to see what this meant from a physical perspective. Basic water hammer can be described as

$$\Delta p = \rho c V$$

Where \(\Delta p\) is the surge pressure, \(\rho\) the fluid density, \(c\) the wave speed and \(V\) the initial fluid velocity. Substituting in the wave speed to this equation will show surge pressure has dependencies on the flow velocity, fluid bulk modulus and fluid density. However, this only describes the internal pressure for the pipe, not the forces applied at bends within the system and importantly the effects on the physical pipe supports.

The basis for the force around a bend is a function of fluid change in momentum and equates simply to a static force element: \((\text{pressure}) \times (\text{cross-sectional area})\); and a momentum term effectively: change in \((\text{density}) \times (\text{flow rate}) \times (\text{velocity})\) over the bend. The forces on the pipes can then be evaluated in a pipe centreline orientation (G values in Figure 2) and resolved to give any resultant force (R value).

Due to the nature of the hydraulic simulator, data on all bend locations was not included in the original model – these have minimal frictional impacts over large systems where bends are well distributed. Therefore, to create a force model, each bend needed locating from site drawings and a reference created for the pressure profile relating to that point in the hydraulic model. Evaluating these specific bend forces gives some insight into local forces, however this approach needed extension to give a better understanding of the physical effects on the system; often the individual bend forces reported were more than the allowable support design loads.

To better understand the force impacts, the computation of bend forces was expanded to include ‘resolved pipe forces’, where the bends at either end of the pipe are resolved to give the resultant effective force in the direction of the pipe centreline. This added much more complexity as the forces (originally just identified at each bend centre) now needed to consider the wider pipe connectivity. This extension included the axial effects of fluid within the pipes; frictional pipe thrust in the direction of fluid flow (generated from interaction between the fluid and pipe wall), diameter changes and inline valves. Special bend cases were also identified to handle features such as ‘tee’ junctions.

Applying Physical Meaning to Bend Forces

The earlier addition of bend forces did not answer all the client’s needs; questions were raised around what the physical meaning of these forces were with regards to resulting stresses on the pipework. Resolved pipe force values were frequently near or above the support design loads, but it was clear that how these forces would apply to the supports was not straightforward.

This led to the use of Dynamic Analysis, using CAESAR II pipework stress analysis software to predict the response of the pipework to the applied hydraulic forces and to understand how the system’s flexibility and restraint conditions affect the pipework’s physical interactions with the existing pipe support work; compared with taking the peak fluid force from the hydraulic analysis. The hydraulic model builds were involved and time consuming; creation of the structural loading models is more so. To maintain client benefit and constrain the cost; the scenarios needed careful consideration and rationalisation.

Bulk Simulation Methodologies

Development of Simultaneous Simulation Runs

In the original scope of the first project, the number of scenarios was small and therefore manageable to be run as individual simulations. As outlined earlier, the complexity and number of potential scenarios soon instigated the need for a means of managing simulations/outputs and running them simultaneously. Ruby was used to script a series of tools enabling interaction with the model parameters, batch run the models and batch export the results into spreadsheets. At the time this was quite an undertaking; multi-threading the simulation processes and managing multiple parametric variations had not been covered much in hydraulic modelling. Alongside the Ruby scripts, the data had originally been
exported to spreadsheets, additional Visual Basic (VB) scripts were generated to collate, arrange and perform basic analysis on the results.

**Rationalising Scenarios**

With a method of dealing with running multiple simulations, the process had gained some efficiency in running multiple scenarios, however there is no substitute to human interpretation when understanding results. Even with the tools created, each simulation results file would have points of interest plotted and the results at least sense-checked. This created a need to rationalise the number of scenarios rather than running all permutations for the benefit of “completeness”. Areas of interest were identifying “worst-cases” – e.g. simulations generating highest flow rates for different sections of the system and comparison of different ESD triggers such as triggering on a ship PERC closure or an out-of-position valve. This meant performing sensitivity analyses and determining the key factors and design elements that contribute to higher pressures and forces.

Moving this data into the Dynamic Analysis to assess the pipework response meant further rationalisation work. The system was separated into sections of similarity. Features such as expansion loops are a regular series of 90° bends creating an Π shape; these are repeated at intervals down the unloading line. Irregular features may be termed as unbalanced bends such as 45° bends leading to 90° bends where the resolved forces at either end of the pipe do not directly oppose each other. The instances of these unbalanced forces continue to present the higher concerns when performing the analysis on this type of site.

The data outputs from the hydraulic and force simulations also needed pre-analysis prior to undertaking the Dynamic Analysis work. To reduce the number of simulation runs and time spent analysing the data, tools were built to pick out the key factors from the bends of interest. For example: all expansion loops were grouped, the results for each similar bend compared against criteria generated from an initial sensitivity investigation. Generally, among other factors, the concept of impulse (or rate of change of the force application) proved a key deciding factor in finding the worst-case force profile. This pre-processing allowed fewer or even singular flow scenarios to be run and identify the thresholds for allowable stresses on the pipework and supports.

**Managing Simulations; Now and Next Steps**

Over many years of projects, small additions, expansions and “special cases” meant there were many steps and caveats to performing these analyses and extrapolating results. Due to the increased detail the transference of this knowledge to other team members became more and more problematic. With improving the usability in mind, the methodology for this type of study was reviewed and a road map of process refinements & simplifications identified.

As described above, the simulation requirements gained much complexity over time and the bespoke tools needed renewing to use more recent software developments. Current work now runs the hydraulic simulation and immediately exports the simulation data to a database allowing more direct and robust interrogation of the data and centralised storage of the results. This then allows comparison of results to previous studies without the need to import them manually and define new comparison scripts.

More recent software developments have also allowed simultaneous and centralised management of simulation runs, providing parameters to be changed at intervals within a specified range and the software generating and running each simulation case automatically. Currently this is mainly run on remote machines and managed on a local level. Of course, technology is never stationary, and this is now moving to the cloud computing model where computational power is greater and can be “spun-up” on an as-required basis. This ecosystem model drastically improves resource/data management with better redundancy and data resilience. More user-friendly analytic tools also come together with this cloud computing, allowing the analysis and presentation of the results from the cloud. Centralised scenario storage is already allowing comparison to cases run many years in the past by purely querying the results database and joining tables, where historically this would have meant collating and joining spreadsheet result pages with potentially different layouts and numbers of pipes/bends.
References


Author Biography

Jonathan Burrows
Mechanical Engineer AMIMechE, DNV GL (Digital Solutions)

Jonathan joined DNV GL in 2014 having previously worked as a Development & Process Engineer in manufacturing. Driving continuous improvement work including development of process models to identify and improve manufacture outputs. Now working in a consulting role at DNV GL Jonathan provides analysis for most hydraulic needs including high level transmission network development through to high-detail AGI analysis. Alongside deskside analysis he is involved in the deployment of operational ‘online’ and trainer systems. He is also involved in digital transformation projects including use of Machine Learning and AI in pursuit of improved client solutions.

Education

MEng Mechanical Engineering, University of Bristol 2011
FIGURES

Figure 1 Simplified Column Separation & Collapse

Rapid Rise in pressure

Fluid momentum over the valve

Fluid velocity slows and momentum 'stretches' the control volume as the valve closes

Fluid momentum 'pulls' a vacuum against closed valve

Returning momentum and rapid phase change cause rapid pressure change

Figure 2 Resolving Pipe Forces

Figure 3 The Evolution of Simultaneous & Batch Simulation