ESD incident evaluation of a crude oil pipeline

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ABSTRACT

A crude oil pipeline transports crude oil from two platforms via a booster station to the terminal; a total distance of over 300 km. The Emergency Shut Down (ESD) incident was initiated by a trip of all pumps in the booster station. Dynamic pressures (and flows) have been recorded by the SCADA system, except for the period of time when the maximum recordable pressure of 100 bar was exceeded. The pipeline operator wanted to ensure that the maximum allowable operating pressure was not exceeded and used this incident to calibrate the pressure surge model including the control systems.

The paper presents the reproduction of this incident and identifies improvements in the control philosophy on the platforms. Review of similar control systems on other platforms may also prove beneficiary. Furthermore this paper illustrates the importance of the dynamic evaluation of long pipeline control systems and several dynamic multi-phase effects in crude oil pipelines.

keywords: pipeline safety, ESD incident, crude oil, transient analysis, multi-phase flow, control system, SCADA, WANDA model.

1. STANDARD CRUDE OIL PIPELINE

The design of this crude oil transportation line and its control systems is very standard. Similar systems are found all over the world. The crude oil transport pipeline comprises two North Sea production platforms (P1, P2) at which most of the gaseous components are separated. The 200 km offshore pipeline transports the oil to an onshore booster station (B1), that lifts the pressure to transport the oil to the terminal (T1). Several hydraulic parameters are listed in Table 1 and Figure 1 below.

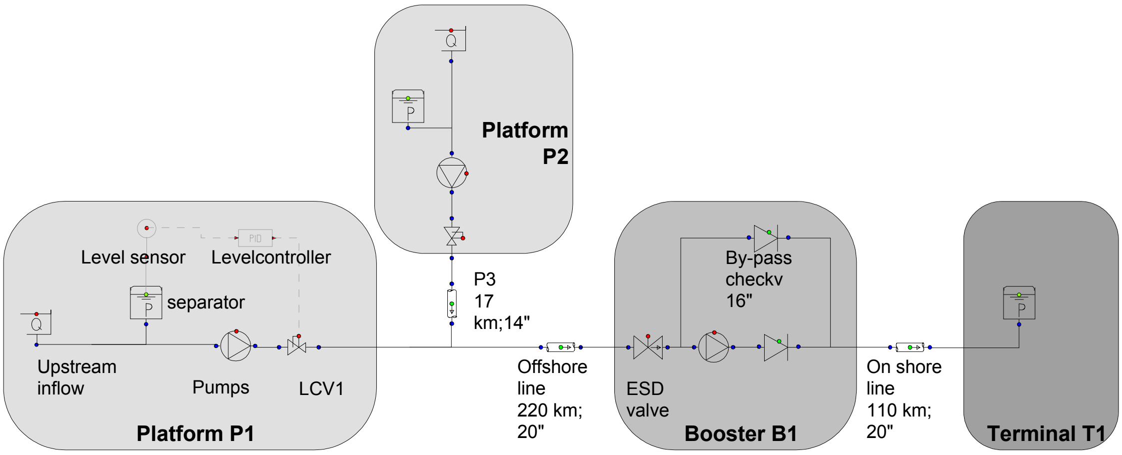

Figure 1: Simplified schematic of the crude oil system

Table 1: System properties

Parameter	Value	Unit
Capacity of pipeline	2370; 358,000	[m^3/h; BPD]
Internal diameter	482.6	[mm]
Nominal line velocity	2.6	[m/s]
Design flow rates P1 ; P2	1920 ; 450	[m^3/h]
MAIP offshore pipeline	119	[bara]
MAIP onshore pipeline	110	[bara]
Nominal discharge pressure P1	77	[bara]
Set pressure booster suction side	4.8	[bara]
Nominal discharge pressure booster	69	[bara]
Set pressure terminal	4.5	[bara]
Crude oil bubble point	0.8	[bara]

The low friction factor that results from the line velocity and pressure grade line (see Figure 2) is established by drag reducing agents (DRA). The SCADA system records flow rates on the platforms and in the terminal. Pressures are recorded on at least 5 locations: the discharge side of the platforms and the booster and upstream of the booster and the terminal.

The control logic on the platforms is as follows. A sufficient number of pumps is running. The Level Control Valves (LCV) on the production platforms throttle the pump discharge pressure in order to control the level in the water/gas separator. This type of control is relatively fast and simple and requires smaller investments than variable speed pumps. The operational cost is generally greater than the operational cost of the variable speed pumps, because the differential head of the LCV's is dissipated. Another (ESD) control loop trips the pumps and closes ESD valves, if a certain set pressure is exceeded. The set pressures on P1 and P2 for pump trip are 97.5 bara. Other control loops for recirculation and single pumpstart/stop are not relevant for the purpose of this paper.

2. INCIDENT

Prior to the incident the flow rate was only 72% (1707 m^3/h) of the nominal capacity. Figure 2 shows the nominal and actual pressure grade line prior to the incident. The friction factor in the simulation model has been tuned to match the actual stationary pressure grade line, because the actual DRA amount and water content were not known exactly. The pressure spikes after 0 km (P1) and 225 km (B1) correspond with the excess pressure of the pumps which is throttled by the LCV on platform P1 and by the pressure control valve (PCV) in booster B1.

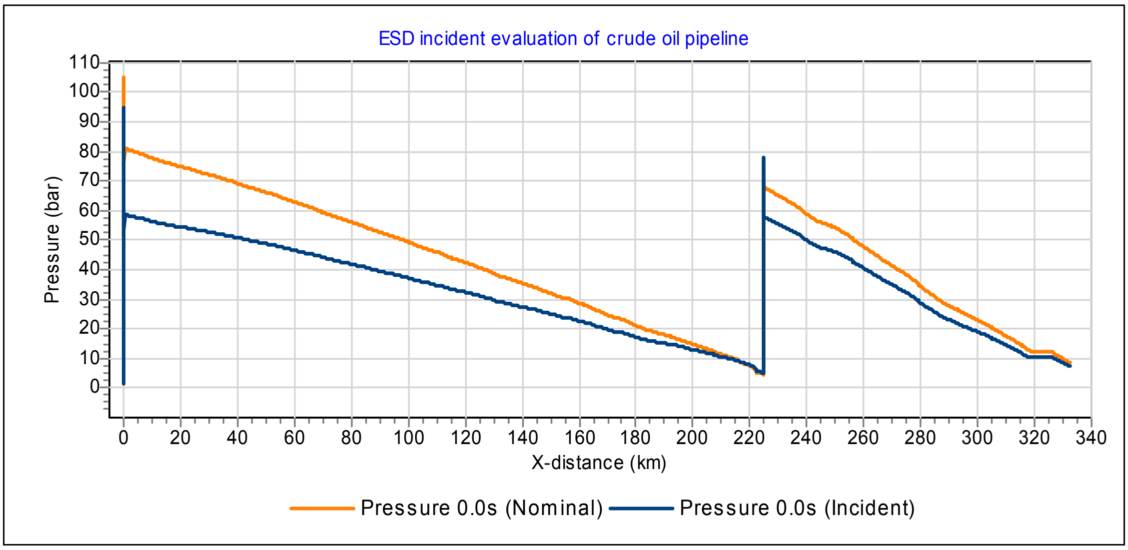

Figure 2: Nominal and pressure grade line prior to incident

The incident started with complete pump trip due to power failure in the booster station B1 and consequential closure of the emergency shut down valves (ESD valves) in B1. The incident was a so-called "full ESD", implying that the by-pass line was shut as well. Figure 3 shows the incident pressures on platform P1 and upstream of the booster station, starting 175 s before the pump trip.

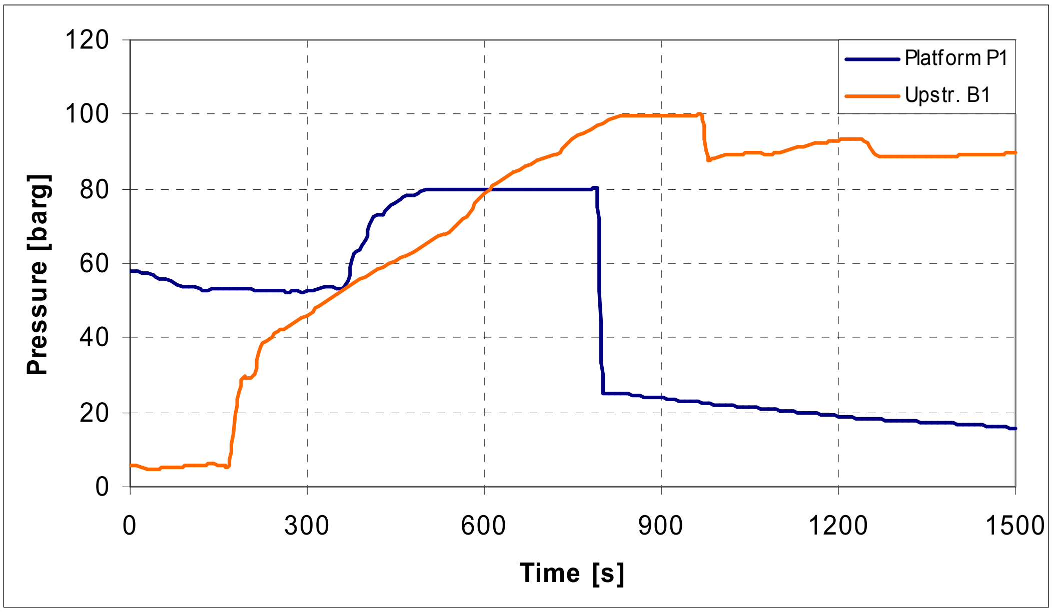

Figure 3: Incident pressure measurements on platform P1 and upstream of the booster

The straight lines at 80 barg on the platform and 100 barg upstream of the booster indicate that larger pressures were not recorded by the SCADA system. The pipeline operator wanted to ensure that the maximum allowable incidental pressure (MAIP) was not exceeded during the incident. Furthermore the operator wanted to ensure that the MAIP would not be exceeded at the design conditions. The client commissioned WL | Delft Hydraulics to evaluate the incident with the transient simulation tool WANDA and to determine the consequences for the design conditions. The project team used this incident to calibrate the existing dynamic hydraulic model including the control systems.

3. INCIDENT EVALUATION

3.1 Offshore line

The WANDA simulation model shows an excellent agreement with the pressure measurements on the platform and upstream of the booster (Figure 4). The booster pumps trip after 175 s (Figure 3 and Figure 4). Then the ESD valves close in 20 s, causing the pressure rise from 5 barg to 35 barg. As the pressure wave travels upstream from the booster to the terminal, line packing is visible upstream of the booster station. The pressure wave needs 190 s to reach platform P1. Now the LCV opens to compensate for the reducing flow rate from the water/gas tank (Figure 5), such that the pressure on the platform rises well above the recorded limit of 80 barg. The maximum simulated pressure is 96.5 barg at which the ESD valve closure and pump trip are triggered. The maximum simulated pressure upstream of the booster station is 108 barg (Figure 4).

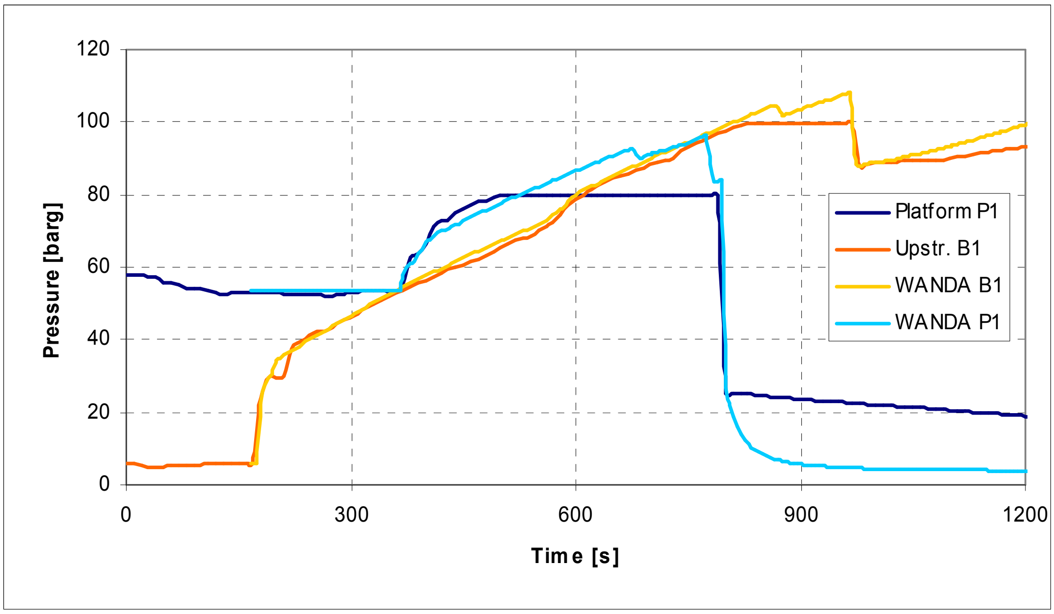

Figure 4: WANDA results compared with pressure measurements on the platform and the booster

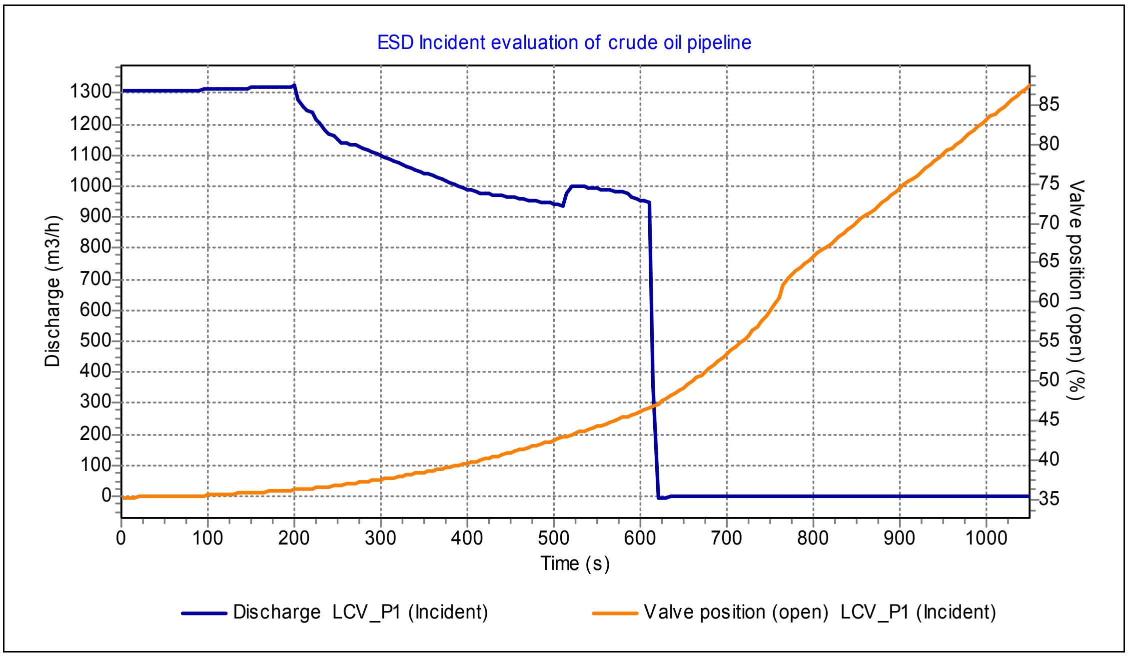

Figure 5: WANDA simulation results - flow rate and LCV position on the platform

The overall maximum pressure in the offshore crude oil line is 110 barg, which is acceptable (see Figure 6).

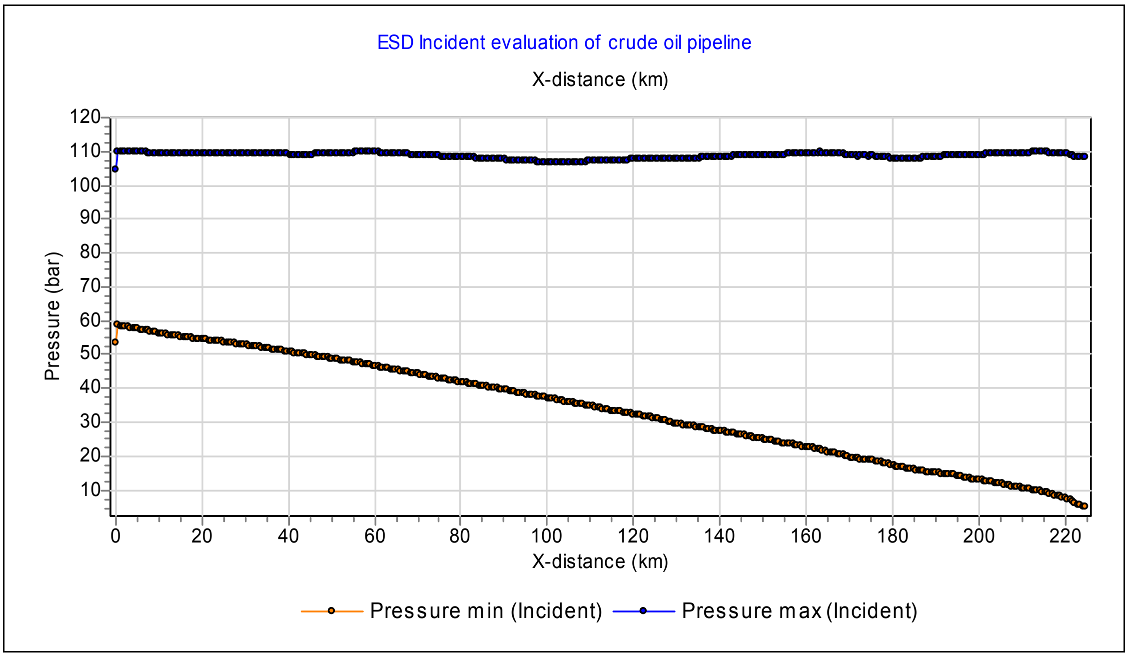

Figure 6: Pressure envelope in the offshore crude oil pipeline

4.3 Onshore line

The onshore part of the pipeline downstream of the booster station suffers a negative pressure transient, during which the pressure drops to the bubble point in the complete onshore pipeline, except the last 15 km (see Figure 7). A significant amount of the lighter fractions come out of solution, especially in the higher sections between 65 km and 90 km (see the profile in Figure 7). The total calculated volume of degassed fractions is about 60 m^3.

It must be noted that the knowledge of the onshore pipeline profile is limited to the profile points in Figure 7, which does affect the reproduction of the incident.

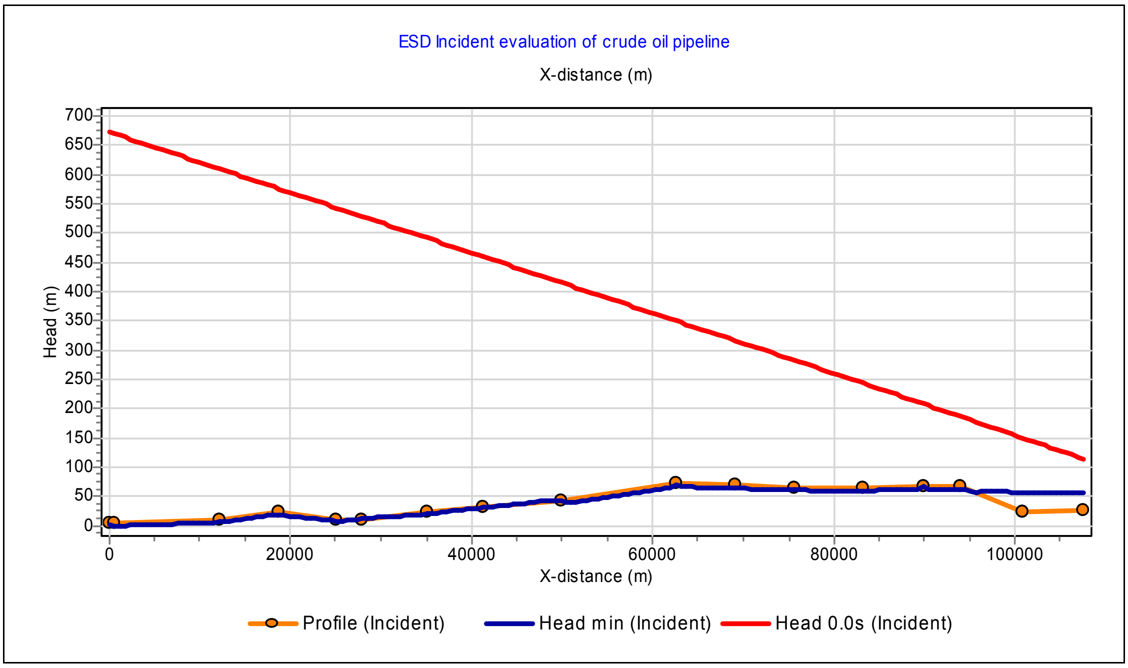

Figure 7: Onshore head envelope and profile

The measured and simulated pressure 10 km downstream of the booster station is shown in Figure 8. The initial transient due to the full ESD and the amplitude of the pressure oscillation are reproduced very well. The timing of the pressure oscillation shows a phase shift.

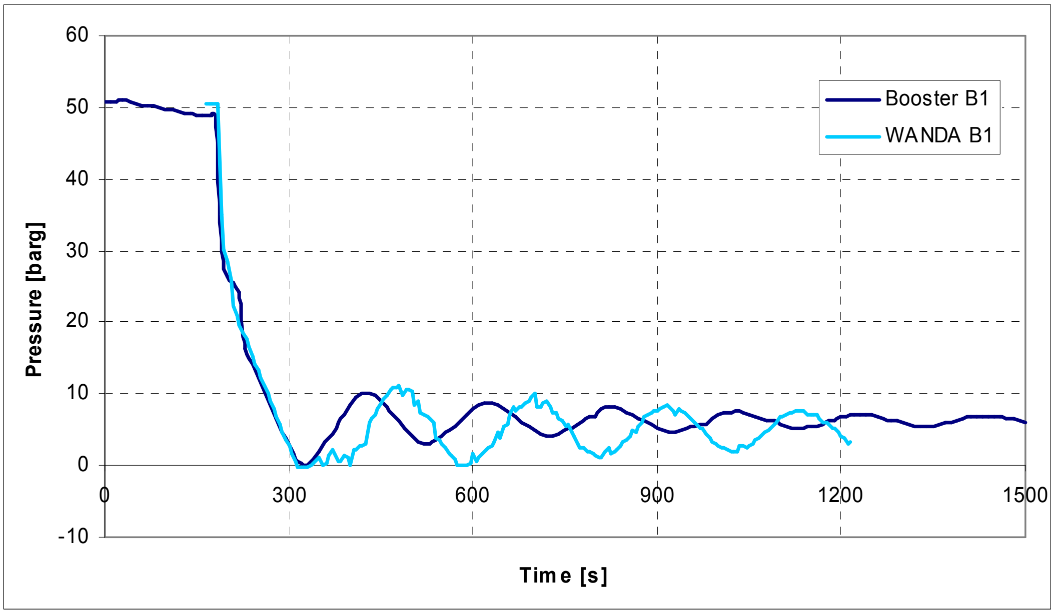

Figure 8: Incident pressure evolution about 10 km downstream of the booster station

The simulated oscillation is introduced by the large degassed volume at the maximum pipeline elevation after 63 km in the onshore line, which generates an oscillation period of 220 s (wave speed is 1170 m/s). The measured oscillation period is 200 s, which would corresponds with a degassed volume after 58 km, which is feasible, given the limited knowledge on the pipeline profile.

Figure 9 shows the measured and simulated flow rate and pressure at the terminal. Different control loops in the terminal were activated during the incident, causing the closure of the terminal control valve after 15 minutes (900 s). The deviation in the terminal inlet pressure may be caused by a reduction in the effectiveness of the DRA, due to the initial flow deceleration, but this is speculative. The WANDA model assumes that the DRA remains effective during the transient.

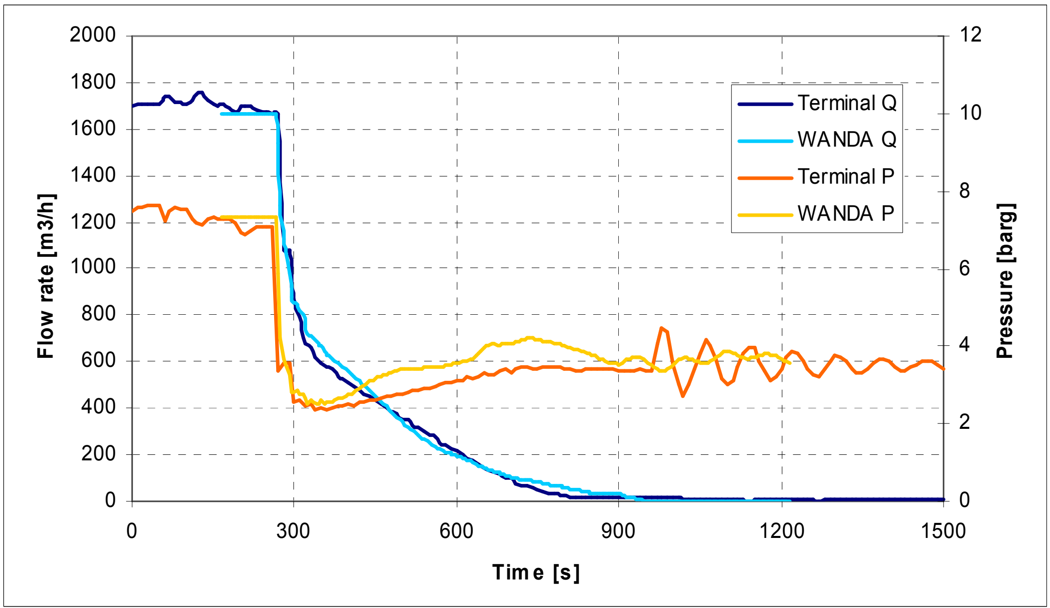

Figure 9: Measured and simulated flow rate (Q) and pressure (P) in the terminal

3.3 "Benefits" of the incident

This incident and its evaluation have provided a thorough verification of the actual control systems on the platforms, in the booster and the terminal, because most of the control system functionality was triggered during the incident. The calibrated WANDA model, including the control systems, has been used to verify the design condition, which proved to be acceptable as well. Furthermore, the WANDA models have been used with increased confidence to verify the feasibility of further upgrades of the pipeline capacity and to propose the required modifications to the control system, in order to operate the system in a safe and cost-efficient way.

4. DISCUSSION

During the ESD incident, the offshore pipeline is unnecessarily pressurised by the LCV opening following the trip of the booster station, because the LCV operates independent of the discharge pressure on the platforms. This pressurisation may be prevented in several ways:

- Add a control loop on the platform to trigger the pump trip and valve closure in an early stage
- Prevent the occurrence of a "full ESD" in the booster station, such that a flow through the by-pass will develop.

The effect of the pressure dependent bulk modulus, which increases about 30% from 2 barg to 120 barg, is discussed in section 4.3.

4.1 Smart ESD control loop on the platform

The set pressure to trigger the ESD on the platform (pump trip and ESD valve closure) is a fixed set pressure of 97.5 bara. During normal operations and slow transients the discharge pressure is related to the flow rate, according to the quasi-steady pressure loss equation. If the difference between the expected discharge pressure (based on the flow rate) and the measured discharge pressure exceeds for example 20 bar, then apparently the booster station has tripped and the platforms should trip as well. This control loop has been included with an accepted pressure difference of 20 bar. Now the maximum pressure in the offshore pipeline is 80 barg only and the ESD on the platform is initiated after 220 s already (was 600 s after start of the event).

4.2 By-pass flow in the booster station

Another feasible solution is to prevent a "full ESD" in the booster, such that a new flow rate through the by-pass will develop. This alternative has been evaluated and the system gradually recovers to its original flow rate, because the LCV in the booster station and on the platform open almost completely.

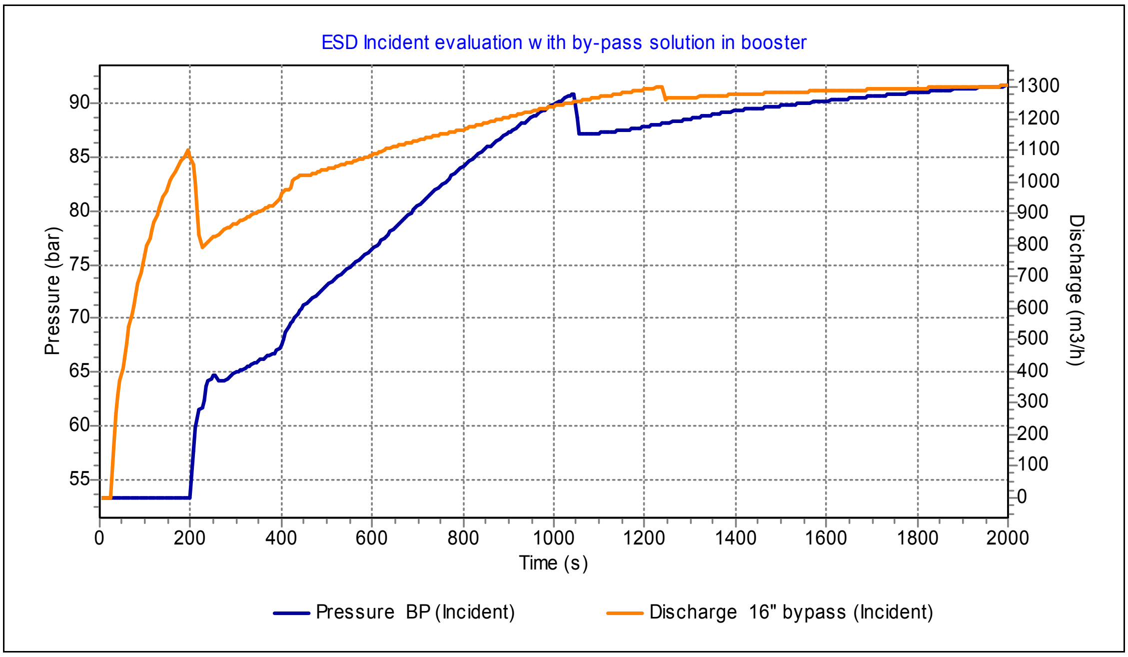

Figure 10: Incident with by-pass flow - Pressure on platform and flow through by-pass

4.3 Variable wave speed

The simulation results above are based on a constant wave velocity. The wave velocity in the WANDA models has been based on the initial pressure on the platform (55 bara). In reality, the bulk modulus of the crude oil increases over 30% when the pressure increases from 2 bara to 120 bara. The pressure dependent bulk modulus increases the wave velocity by about 10% (Table 2).The variability in the wave velocity has been verified and has a marginal impact on the simulation results.

Table 2: Wave velocity at different pressures

Pressure [bara]	Oil bulk modulus [GPa]	wave velocity [m/s]
2	1.23	1083
35	1.39	1144
69	1.53	1185
103	1.58	1200
121	1.60	1204

5. CONCLUSIONS AND RECOMMENDATIONS

If the level controller on a production platform is not linked to the platform's discharge pressure, then the control system is practically a flow controller, which tends to maintain the upstream multi-phase flow rate after any downstream ESD procedure.

The reliability and required pumping energy of a production platform will improve, if the control system of the platform takes into account that the platform's discharge pressure is coupled with the flow rate. This solution triggers the ESD procedure on the platform in an early stage, such that the maximum pressures are significantly reduced from 110 barg to 80 barg in this particular situation.

Another feasible solution is to prevent a "full ESD" in the booster station, such that the platforms can continue their production.

The incident evaluation confirms that WANDA is perfectly suitable for simulation of critical transient events in these kind of systems including control loops. Dynamic hydraulic models, as built with WANDA, should not only be used to address safety issues, but also for all kinds of operational optimisations. Currently such models are only used during the detailed design stage to size anti-surge provisions or to verify normal operations and emergency procedures. However, accessible dynamic hydraulic models can be used to settle the as-built situation of the pipe system and control systems. Such models should be calibrated during commissioning tests. An upgrade of the system capacity or temporary modifications to the hardware or the control system are easily verified on the design scenarios, if such calibrated dynamic hydraulic models would be available.

Acknowledgements

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References

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