The effect of density waves and slurry dynamics on slurry pipeline flow assurance cannot be predicted with current slurry pipeline design methods. Current methods are based on steady-state assumptions, assuming that the mixture velocity and density are constant in time and in the pipeline. Therefore, using current design methods a dynamically stable pipeline cannot be guaranteed. Furthermore, new experiments in vertical pipelines show that density wave amplification is possible at mixture velocities far above the critical velocity. This article presents a new temporal design method based on 1D Driftflux CFD, which is able to model growing density waves.

For many years, dredging pipelines have been designed with steady-state models for the energy losses in a pipeline and the energy added by the centrifugal pumps. The design of a hydraulic transport system starts with a criterion for the capacity of the pipeline, in how many sediment the system needs to transport per unit time. Following this, the designer needs to determine the pipe diameter, by estimating the magnitude of energy lost by the slurry as it flows through the pipeline, and the energy generated by the centrifugal pump(s) to drive the system. This is typically done using a steady-state analysis, where it is assumed that the mixture velocity and sediment concentration in the pipeline are constant in space and time. However, a steady flow and concentration are only possible in laboratory circuits and is not representable for the concentration distribution in field pipelines during dredging operations. This is due to the cyclic nature of the sediment feed of dredging pipelines, for instance the swaying and stepping of a cutter suction dredger.

The steady-state design method looks at the intersection of the pump pressure curve and the pipeline frictional losses curve (see Figure 1). The intersection between these two curves is the mixture velocity at which the pipeline will operate (the “operating point”) at a given steady concentration. Any changes of the sediment concentration in the pipeline, or flowing through the pump, will cause the operating point to shift, resulting in mixture velocity variations. Both characteristic curves of the pump pressure and mixture frictional losses are typically determined in laboratory circuits under steady conditions.

The operating velocity should be above the critical velocity to avoid blockages and below the vacuum limit to avoid cavitation. The critical velocity is defined as “the minimum velocity required for transport of solid material through a pipeline without any particle deposition” (van den Berg and Stam, 2013). The final design includes an estimation of the number of pumps, the required power for the
The critical velocity is the preferred safety limit for dredging pipelines. If the operation velocity of a pipeline drops below the critical velocity, the pipeline will block, unless an operator intervenes. This process of pipeline blockage is in its very nature a transient and temporal process that is caused by the minimum in the resistance curve, which defines the critical velocity. Because when the mixture velocity drops below this minimum, the pressure losses will increase, which slows down the mixture. Therefore, more particles will settle out of suspension (if the sediment feed of the pipeline remains unchanged), further increasing resistance and causing the velocity to decrease once more, and more particle settle out of suspensions, etc. To conclude, the process of pipeline clogging is a transient and temporal process and for long pipelines this process can be slow, where the only indication is that the average mixture velocity slowly drops over time. This can be difficult to detect considering typical fluctuations of the mixture velocity. The pipeline blockage process can be reversed by slowly lowering the sediment feed into the pipeline and allowing the mixture velocity to increase. The steady-state design method is suitable to investigate the maximum loading case of a pipeline and its components. However, even when complying to this design methodology, the formation and amplification of density waves is still a common occurrence in the dredging industry and comprises the efficiency and safety of operation (Matoušek, 1997), especially for long pipelines. Density wave amplification is also a large risk for cheaper small diameter pipelines, which typically do not have the same level of monitoring as their larger cousins. Furthermore, recent advances into deep-sea mining hydraulic transport technology has uncovered a density wave amplification mechanism caused by a different mechanism (de Hoog et al., 2021). To better understand the density wave amplification effect and in general, the effect of transients on pipeline stability, a better temporal design methodology is needed.

In this article, we briefly explain the cause of density wave amplification and its effect on pipeline operation. We introduce the mathematical foundation of a 1D CFD model that can be used to study the effect of time domain processes on the stability of pipelines and the growing of density waves. Finally, an outlook on what can be studied and achieved with a 1D CFD model, such as a temporal stability analysis, feedback controller design and quantifying maximum load for the design of dual fuel and fuel cell based drives, which are the drives of future dredgers.

**Density wave amplification**

The growth of density waves in a pipeline is a result of the redistribution of soil from one part of the flow towards another. This can occur even if the soil was injected relatively steady over time. The redistribution of material has been identified to occur under two circumstances (de Hoog et al., 2021). Firstly, redistribution can be caused by deposit formation in the pipeline, which occurs when the pipeline operates with a fluctuating mixture velocity and with an average velocity close to (but above) the deposit limit velocity. This will typically be the case for long pipelines that do not have flow control to keep the mixture velocity steady. The second type of redistribution mechanism was observed for mixture velocities far above the critical velocity (and therefore above the deposit limit velocity), in systems with pipes at different orientations and therefore axial variation of particle velocities. This section briefly explains two case studies that were subject to density wave amplification.

Density waves in horizontal long pipelines

Density wave growth in pipelines remains a common occurrence in the dredging industry, especially with longer pipelines with booster stations. In some cases, density wave growth leads to flow assurance issues. Unfortunately, these cases are not often reported publically. The only publicly reported case was the Prins Clausplein pipeline, used to construct the equally named highway junction near The Hague, in the Netherlands. This pipeline was 10 kilometres long, 650 mm in diameter and had three booster stations, transporting medium to fine sand. The particle size distribution of the sand was very wide, with 12% smaller than 75 μm and 7% larger than 700 μm. The mass medium particle diameter varied in time between 150 μm and 500 μm.

Figure 2 shows an example of data recorded during operation of this pipeline. The top graph shows the measured mixture velocity of the pipeline over time, which was measured at the booster station Jagersplas located at 1886 metres along the pipeline. The three remaining graphs show the measured mixture density at the start of the pipeline (the dredger Groningen) and at 1886 m and 6538 m along the pipeline at boosters Jagersplas and Duinjager respectively. Note: the time axis of the graphs are shifted in time with respect to each other to visualise the development of density waves. The sediment injected at the start of the pipeline is relatively steady varying.
between 1000 and 1500 \( \text{kg/m}^3 \). However, at Jagersplas the mixture entering the system between 14.30 and 15.30 hrs had diluted considerably and this same part of the mixture at Duinjager consisted almost exclusively of water. The sand had relocated towards different parts of the flow and accumulated into density peaks. The accumulated material was found back in density waves measured by Duinjager between 16.00 and 16.30 hrs. The same event occurred for sediment entering at 16.30, found back in density peaks at Duinjager from 17.00 to 18.00 hrs.

Because the pipeline was troubled by density wave amplification, this case study was investigated by Matoušek (1995) and Matoušek (1996a, b). Initially the cause was thought to be an axial variation in particle velocity, as a function of the mixture concentration. More specifically, high-density waves travel faster than low-density parts of the flow and high-density waves would overtake lower densities. However, Talmon (1999) and de Hoog et al. (2021) show that this is not the case. Specifically, axial velocity variations do exist, due to concentration variations (as measured by Matoušek [1996a]), but causes damping of density waves and not amplification. Talmon (1999) first introduces the hypothesis of an unbalance between sand sedimentation and erosion from a stationary deposit. The result of the unbalance is that, at a sufficiently high velocity (around the deposit limit), high-density parts of the flow erode deposits, while low-density parts create deposits. This process is mathematically proven by Talmon (1999), experimentally investigated in Talmon et al. (2007) and further explained by de Hoog et al. (2021). This effect causes material to be redistributed into high-density waves if deposits are present in the pipeline. The axial velocity variations (due concentration variations, as measured by Matoušek [1996a]) causes the peak of the density wave to propagate forward, since the particle velocity is higher at higher concentration. Under these circumstances, the amplification effect of the erosion and sedimentation unbalance is stronger than the relatively weak damping effect of axial velocity variations. Therefore, the net results is amplification. Amplification ceases once the deposit has been fully eroded.

Whether a deposit is formed depends on the local concentration and the global mixture velocity, due to the erosion and sedimentation unbalance. These deposits were present, because the Prins Clausplein pipeline operated close to the deposition limit velocity, and sporadically dropped below due to fluctuations in the mixture velocity. This created sporadic deposits, which were entrained into density waves, due to the erosion and sedimentation unbalance. These density waves passed through the boosters and created more mixture velocity fluctuations and thereby new density waves. This interaction continued to initiate density wave amplification. For a more detailed explanation of the process, see de Hoog et al. (2021). To conclude, the Prins Clausplein pipeline formed density waves because the mixture velocity fluctuated and sporadically dropped below the deposit limit velocity. Therefore, maintaining a mixture velocity above the deposit limit velocity should avoid the amplification of density waves, and thereby keep the system stable. Even better is if the mixture velocity is maintained at a constant level by means of feedback control.

### Density wave amplification above the critical velocity

For the development of vertical transport technology to be used for deep-sea mining, a 297 metre-long vertical pipeline system was constructed in the summer of 2017 by Royal IHC and TU Bergakademie Freiberg, in Halsbrücke, Germany. This 150 mm diameter flow loop was partially constructed in a vertical mineshaft, which facilitated a 121 m vertical downgoing pipe and riser. These two vertical pipes were connected to 57 m of horizontal pipes at the top of the flow loop, containing the dredge pump and sediment injection systems. For more details of the setup, see Mueller et al. (2018). Experiments were conducted with two graded sediments: \( d_{50} = 600 \, \mu m \) sand and \( d_{50}=112 \, mm \) gravel. The sediment volumetric concentration was varied as part of the experimental program at 5\%, 10\% and 15\%.

Figure 3 shows a schematic overview of the measurement system. Measured parameters were: the delivered concentration \( C_{\text{cut}} \) (the ratio between the particle flow rate \( Q_p \) over the mixture flow rate \( Q_m \), measured with a U-loop pressure measurement between p11...p14), the mixture concentration with a conductivity concentration meter (CCM), the mixture velocity, various pressure sensors along the riser, pump pressure, pump revolutions and drive power. Figure 4 shows an illustration of the pipe circuit and the vertical mineshaft.

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**FIGURE 3**

A schematic overview of the sensors and the flow loop. The flow direction is from right to left through the pump.

**FIGURE 4**

A detailed illustration of the Freiberg pipe circuit, showing the topside equipment and the vertical mineshaft with the riser and downgoing pipe.
Density waves can occur at mixture velocities far above the critical velocity.

During the tests density wave amplification was a common occurrence. Almost all experiments showed density wave amplification. The experiments at higher concentration required too much power from the pump drive and therefore these tests had to be ended prematurely (due to the growing density waves). An example of a test with gravel at a volumetric concentration of 10% is given in Figure 5. As part of the experiment procedure, the pump revolutions were kept constant for several minutes and lowered during a few intervals as part of the test. The aim was to acquire data at several constant mixture velocities. However, even though the pump revolutions were kept constant for long periods, the mixture velocity fluctuated as density waves kept growing with each circulation through the loop. Figure 6 shows an experiment with sand, which was initially stable at low concentration (5%) and at high velocity. However, after filling the system to 10% the density wave growth rate significantly increased while the pump revolutions were kept constant over a period of half an hour. The resulting density wave length for all experiments was similar to the system’s length.

Transient accumulation in the Freiberg flow loop
The alarming aspect of density wave amplification witnessed in the Freiberg circuit, is that amplification took place at mixture velocities far above the deposit limit velocity and the critical velocity. This is unlike in the Prins Clausplein pipeline, where amplification stops when the mixture velocity remains above the deposit limit velocity. Therefore, the cause of density wave amplification in the Freiberg system is hypothesized to be caused by a different process.

Specifically, the difference in particle velocity between the horizontal and vertical pipelines is thought to contribute to density wave amplification. Particles travel slower in the horizontal pipelines. Therefore, when a density wave flows from the riser into the horizontal pipeline, the material accumulates temporarily and increases in concentration (as continuity dictates). This can be described with the following spatial continuity equation:

\[
\frac{\partial}{\partial x} (c \cdot v_x) = 0
\]  

(1)

Where \( c \) is the volumetric concentration in a pipe, \( v_x \) the particle velocity and \( x \) the axial coordinate of the pipe. Figure 7 shows a comparison between the particle velocity \( v_x \) in horizontal and vertical pipes for the Freiberg flow loop. For the horizontal pipes, the particle velocity can be calculated from empirical relationships of the slip ratio \( R_s \), which is the ratio of particle velocity \( v_s \) over the mixture velocity \( v_m \) [also known as the transport factor]:

\[
R_s = \frac{v_s}{v_m}
\]  

(2)

The slip ratio is an empirical relationship, measurable in a laboratory and available in academic literature (although very uncommon). Examples of academic models are for instance the slip ratio from steady-state two-layer models (Wilson, 2006; Matoušek et al., 2018), or from empirical relationships (Miedema, 2015; Sobota and
In the illustrative example of Figure 7 the slip ratio model of Sobota and Kril (1992) was applied for the horizontal pipe. For vertical pipes the solids velocity $v_s$ is modeled according to the hindered settling principle (Richardson and Zaki, 1954):

$$v_s = v_m - w_{ts} (1 - c)^n$$

Where $w_{ts}$ is the terminal settling velocity of a particle, $c$ the average volumetric concentration and $n$ the Richardson and Zaki (1954) settling exponent. For the illustrative example in Figure 7 the settling parameter $n$ is modeled according to Garside and Al-Dibouni (1977) and $w_{ts}$ is calculated according to Ferguson and Church (2004) for angular natural grains.

In the Freiberg loop, the slurry flows from a vertical riser into a horizontal pipe. Let us assume the mixture velocity is steady in time and all concentration variation have been damped out apart from one density wave travelling up the riser. As this wave flows from the riser into the horizontal pipe, the particle velocity decreases. This is illustrated in Figure 7, where the particle velocity drops from point 'a' to point 'b'. Continuity dictates that the concentration must increase during this event (Equation 1). This in itself is only a temporarily increase of concentration, because once the mixture would flow again into a vertical riser, the particle velocity returns to its original state (from point 'b' to 'a' in Figure 7). Hence, the concentration decreases and recovers. The concentration increase was only temporary.

The key to understanding density wave amplification in Freiberg is that the mixture velocity also increases as the density wave flows out of the riser and into the horizontal pipe. This is due to the working nature of a centrifugal pump, which does not operate at a constant velocity. Once the density wave flows out of the riser, the load on the pump decreases due to the decreasing in hydrostatic gradient. As this happens, the particle velocity goes from point ‘a’ to ‘b’, towards ‘c’ in Figure 7. Once the wave flows out of the horizontal pipe, the velocity increase is smaller, from point ‘c’ to ‘d’ in Figure 7. Consequently, part of the increased concentration remains. Note that the path from ‘b’ to ‘c’ does not cause a concentration drop, as this does not coincide with a pipe orientation change, therefore $\frac{\partial n_s}{\partial x} = 0$ (whilst $\frac{\partial v_m}{\partial x} > 0$). In the Freiberg system, the density wave flows into to the downgoing pipe once leaving the horizontal pipes before flowing into the riser again. This increases the mixture velocity even further and strengthens this effect. The above explains the working principle behind the transient accumulation hypothesis.

To conclude, density wave amplification in the Freiberg loop is hypothesized to be caused by:

1. a difference in particle velocity when the slurry flows from vertical to horizontal pipes;
2. a coincidental increase in mixture velocity due to working principle of a centrifugal pump. This velocity difference between vertical and horizontal pipes is smaller at high mixture velocities and at lower concentration. Therefore, under these conditions amplification should not occur, or if it does, the growth rate should be lower. This trend was indeed witnessed during the Freiberg experiments, which supports the transient accumulation hypothesis.

Transients slurry pipeline modelling

The ability to conduct a time domain analysis of a pipeline, and predict density wave amplification, allows a designer to understand these processes better and to investigate methods to avoid density wave growth. To achieve this goal, a full transient model is needed since the pipeline configuration and pump positioning could potentially influence stability, thereby this interaction can become very complex. By using multiphase computational fluid dynamics (CFD), to resolve the particle phase and fluid phase separately, these goals could be achieved. From these findings, we can derive that three key aspects need to be incorporated into the CFD model:

- The particle velocity, as a function of concentration, mixture velocity and pipe orientation (i.e. vertical or horizontal).
- Model stationary deposits, so that density wave amplification in horizontal pipelines can be predicted, as witnessed in the Prins Claus pipeline, and
- A pressure driven solver, to model the pressure provided by the centrifugal pump(s). The pump pressure should be a function of the mixture flow rate, mixture density and particle diameter. The pressure source can numerically be manipulated to model the pump and drive behaviour, and mimic a control feedback system.

Pipelines can be kilometres long; therefore, 3D and 2D simulations are too computationally expensive, as are state-of-the-are discrete particle techniques like CFD-DEM. A long pipeline, where its radial dimensions are very small compared to the axial dimension, lends perfectly to a 1D continuum model. The value and potential of a 1D Driftflux model (or “mixture model”) has already been explored.
Particle transport equations

The proposed model needs to model stationary deposits, which can be achieved with a two-layer model. The lower layer will always be stationary and will therefore not need its own transport equation. The transfer of mass, between the lower stationary layer and the upper flowing layer, will be modelled with a source term. See Figure 8 for a visualization of the structure of the model.

The 1D-2L-HT CFD model is based on the Drift flux or Mixture model [Ishii and Hibiki, 2006]. The Drift flux model can model a fluid and a solid phase with a velocity difference, based on the assumption that the particle inertia is small and particles instantly follow changes in the fluid field. With this assumption, only one momentum equation is needed for the entire mixture. This mixture’s continuity equation equals:

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial}{\partial x}(\rho_m \hat{v}_m) = 0 \quad (4)$$

Where $\rho_m$ is the mixture density and $\hat{v}_m$ the mass flow rate based mixture velocity:

$$\hat{v}_m = \frac{\rho_F}{\rho_m} v_F + \frac{\rho_F}{\rho_m} v_F(1 - c) \quad (5)$$

In the equation above, $\rho_s$ is the solids density, $\rho_F$ the fluid density, $v_F$ the solids velocity, $v_F$ the fluid velocity and $c$ the volumetric concentration of solids. The changing cell volume, due to the two-layer structure, requires special attention in the numerical derivation of the transport and momentum equations. Applying the finite volume method on the schematic presented in Figure 8, and taking into account the changing cell volume, results in the following transport equation (Hirsch, 2007):

$$\frac{\partial}{\partial t}(c \cdot \Delta V) + \sum_{faces}(F \cdot \Delta A) = \Gamma \quad (6)$$

With $c$ the cross section averaged volumetric concentration of the upper layer, $V$ the volume of the cell area above the bed layer, $F$ the cell face fluxes, $A$ the cross sectional area of the upper layer and $\Gamma$ the bed layer erosion and sedimentation source term.

The cell face fluxes are modelled as:

$$F = v_s c \quad (7)$$

with the particle velocity

$$v_s = v_m + v_{s/m} \quad (8)$$

where $v_{s/m}$ is a relative velocity model, to model the velocity differences between the solids and the fluid. In Equation 8, $v_m$ is the volumetric based mixture velocity:

$$v_m = \frac{\rho_F}{\rho_m} v_F + \frac{\rho_F}{\rho_m} v_F(1 - c) \quad (9)$$

In Equation 9, $v_s$ is the solids velocity and $v_F$ the fluid velocity. The relative velocity model for horizontal pipes will be based the slip ratio $R_s$ (Equation 2):

$$v_{s/m} = v_m(1 - R_s) \quad (10)$$

The solids velocity in the vertical pipes is modelled with Equation 3.

Modelling stationary deposits

Equation 6 needs a closure relationship for the bed source term $\Gamma$. The erosion and growth of the lower bed layer can be approximated using erosion and sedimentation models, like those used by van Rijn (1986) and van Rhee (2010). The vertical velocity of the top of the bed $v_b$ is modelled as:

$$v_b = \frac{S - E}{\rho_s(1 - c_n_b)} \quad (11)$$

where $S$ is the sedimentation flux, $E$ is the erosion flux, $c$ is average volumetric concentration of the eroding flow and $n_b$ the porosity of the bed. The source term $\Gamma$ becomes:

$$\Gamma = v_b c_b \Delta x W \quad (12)$$

with $c_b$ the bed concentration, $\Delta x$ the cell size and $W$ the width of the bed layer top. The sedimentation flux

$$S = \rho_s w_{ts}(1 - c)^n \quad (13)$$

is based on settling velocity of the particles, $w_{ts}$. Additionally, for high concentrated flows the hindered settling principle must be used to correct the settling velocity, through the hindered settling exponent $n$ [Richardson and Zaki, 1954]. In a pipeline, the flow over the bed layer is high, therefore the erosion model $E$ should be suitable for high velocity flows. Since high flow velocities create a shear layer zone on top of the sediment bed, where dilatancy reduces the erosion rate [van Rhee, 2010]. Fortunately, recent research provides experimental data and models specific for erosion at high flow velocities by Bishop et al. (2016) and van Rijn et al. (2019), however these models have not yet been applied in pipeline flows. Therefore, the suitability of erosion and sedimentation models in pipeline flows requires further investigation and will be part of future work.

Mixture momentum equation

To model the interaction between resistance forces caused by the slurry and driving forces from the centrifugal pumps, a 1D variation of the Drift flux momentum equation can be used. The differential form of the momentum equation is given in Equation 14. As with the transport equation, the changing cell volume needs to be included in the momentum equation, as time and spatial derivatives of the cross sectional area of the cells.
In Equation 14, $\rho_m$ is the mixture density, $P$ the pressure, $r_m$ the mixture resistance on the pipe wall, $\tau_k$ the shear force over the bed layer, $O$ the circumference of the upper layer, $W$ the width of the bed layer and $\omega$ the pipe inclination angle. The last term in Equation 14 is an inertia coupling term, which is required to correct for the exchange of momentum between the solids and the fluid when they are subject to a velocity difference. The pump pressure can be modelled as a boundary condition when solving the pressure Poison equation (which follows from Equations 4 and 14). Alternatively, multiple pumps can be modelled by adding an additional term in Equation 14 (van Wijk, 2016), however this does require a numerical solver that can cope with large momentum gradients.

Equations 4, 6 and 14 form the foundation of the 1D-2L-HT model. A great benefit of the model structure is that it allows for the simulation of a pipeline system with pipes at all possible orientations, as long as the slip ratio model and the wall friction model are a function of the pipe orientation. For vertical pipes, the two layers are not needed. Thus, with one solver a complex system can be simulated with pipes at various orientations. The main numerical challenges lie in the correct implementation of erosion and sedimentation models, and the changing cell volume of the upper layer above the bed.

### Preliminary simulation results

Figure 9 shows preliminary results of simulations of the Freiberg system. In this case study, the mixture velocity is always above the critical velocity. Therefore, stationary deposits are not present and the two-layer structure of the 1D-2L-HT is not necessary. The pump pressure was modelled using the pump curve of the actual pump used in Freiberg at a fixed RPM. The use of a pump curve at a fixed RPM results in a dynamic mixture velocity. Modelling the pump curve, together with a velocity difference between the horizontal and vertical pipes, is key in order to simulate density wave growth. The results presented in Figure 9 are preliminary, proper validation and matching with experimental data will be published as part of future work.

The Sobota and Kril (1992) and the hindered settling principle was applied to model the particle velocity for the horizontal and vertical pipes, respectively. The pipeline resistance $r_m$ was modelled with the equivalent liquid concept, where the mixture is modelled as a Newtonian fluid with increased density. This equivalent liquid model is at the moment a placeholder model. A more suitable model, representative of actual flow conditions, will be applied in follow-up research.

The following similarities between the simulation and the data can be identified:

- The time for the density wave to grow is of similar order;
- The waves are formed into distinct saw tooth shaped waves;
- Density wave growth occurs above the critical velocity; and
- The wavelength equals the system length.

To conclude, the preliminary results show that the 1D-2L-HT model is capable of capturing the interplay between the pump dynamics, particle velocity changes and pump load variations, which cause density wave amplification in the Freiberg system. This fact that this preliminary results show good agreement with the measured data supports the validity of the transient accumulation hypothesis.

### Discussion of model application

#### System stability analysis

The main application of the 1D-2L-HT model, as described previously, is to evaluate if and how a pipeline system becomes unstable due to transients. The model allows the designer to study the effect of complex changing load dynamics with non-steady sediment inflow conditions. An example is a pipeline system that needs to ascent over a large hill. The hydrostatic mixture gradient is large compared to fictional losses, therefore a non-uniform spatial concentration distribution will cause the pressure delivered by the pump to fluctuate severely when density waves flows up the hill, thereby cause fluctuations of the mixture velocity. If due to these fluctuations, the mixture...
velocity drops below the deposit limit velocity, density waves could amplify as was the case in the Prins Claus pipeline.

Pump positioning could potentially influence the stability analysis of the system. Continuing with the fictional pipeline above, when a booster pump is placed at the foot of the hill, the booster could help push the density wave upwards, since the pressure delivered by the pump increases when the mixture density flowing through the pump increases (Wilson, 2006). De Hoog et al. (2021) concludes that the booster stations in the Prins Clausplein pipeline contributed to velocity fluctuations, which initiated new density waves. Positioning all boosters at the start of the pipeline could solve this problem. Even if density waves do amplify, they will no longer flow through a booster and no longer cause the mixture velocity to fluctuate. This hypothetical solution, of intelligent booster pump positioning, can also be investigated using the 1D-2L-HT model. The pressure rating of the pipeline at the boosters should be high enough to allow for this solutions.

The Freiberg system instability is hypothesized to be caused by a difference in particle velocity between vertical and horizontal pipes, coinciding with an accelerating mixture velocity due to centrifugal pump dynamics. The particles travel slower in horizontal pipes, causing “transient accumulation”. The particle velocity can be matched better with the vertical pipe by lowering the diameter of the horizontal pipes. Whether this is a valid solution can be investigated with the 1D-2L-HT model. For this specific case, the two-layer structure is not needed as density waves in the Freiberg system amplified at mixture velocities far above the deposit limit velocity and a stationary bed was not present.

Controller design
A consequence of density waves is a fluctuating mixture velocity. Furthermore, de Hoog et al. (2021) speculate that feedback control, to keep the mixture velocity steady, could significantly help in stabilising the system. The 1D-2L-HT model can be extended with a simulated feedback control system, as done by van Wijk (2016). This application is especially useful for horizontal pipes, where density waves are formed rapidly if the mixture velocity drops below the deposit limit velocity. Therefore, maintaining a constant mixture velocity at a safe margin above the deposit limit velocity will avoid density wave growth. However, feedback control is only possible if the drive power has a margin and preferably with an electric motor, which can be controlled more easily. The 1D-2L-HT model can be used to investigate the magnitude of the drive power margin that is needed to facilitate feedback control, and to check whether the control system is able to respond fast enough to maintain a constant flow rate.

Diesel driven pumps have a smaller control range and are therefore more difficult to control. Diesel drives are still commonly applied in smaller and cheaper pipelines. Furthermore, feedback control is only possible in the presence of a flow meter, which is often absent in cheaper pipelines. With the 1D-2L-HT model an alternative of flow meter feedback can be investigated, for example one based on significantly cheaper pressure sensors.

Dynamic drive load analysis for dual fuel and fuel cell drive design
The reduction of drive emissions is probably the current single most discussed topic in the maritime industry, driven by the uncertainty of oil and gas prices and more strict emission legislations (Shi et al., 2015). In the dredging industry, the first dual fuel (DF) dredgers have been built using liquefied natural gas (LNG). These drives reduce the emission of harmful gasses, but are challenging to integrate in a dredging vessel due to the large dynamic loads associated with dredging operations. More specifically, the dual fuel drives switch from the cleaner gas operating mode to a diesel operating mode during heavy transient loads that consequently increases harmful emissions (Mestemaker et. al., 2020). Furthermore, some prime movers such as spark-ignited (SI) engines do not have the ability to switch back to a diesel operating model and will therefore fail. Consequently, the centrifugal pump stops and the slurry pipeline comes to a halt. One solution, to allow DF and SI drives to cope with high transient loads, is an energy buffer to provide energy during these transient events. In addition to DF and SI drives is fuel cell based drives. The fuel cell based drive is a popular and actively researched drive technology for the future. However, this drive needs an even larger energy buffer to cope with transient loads. The 1D-2L-HT model can be used to simulate a slurry system, thereby to quantify and simulate realistic transport conditions where dynamic loads are highest. For a trailing suction hopper dredger, these highest loads (of the entire vessel’s drive train) are experienced when the dredger is discharging on a long land pipeline. Since in addition to the power required by the dredge pumps, the fluidising of sand in the hopper requires a large amount of power for the jetting pumps. A transient analysis of the drive (Mestemaker et. al., 2020), with loads simulated with the 1D-2L-HT model, allows the drive designer to ensure continuity of the power train and thereby flow continuity of the pipeline and optimal operation of the dredger.

Conclusions
Steady-state design methods to design hydraulic transport pipelines have their limits and cannot predict the stability of a pipeline with a highly fluctuating mixture velocity. This can lead to the amplification of density waves and compromise the safety and efficiency of the pipeline. When these fluctuations drop below the critical velocity, density waves are formed, further impeding the flow of the pipeline. Even if the mixture velocity is above the critical velocity, transients can lead to an unstable system due to density wave amplification, as seen in Freiberg. To study the transient stability of pipelines, a 1D-2L CFD model is proposed with variable particle velocity and dynamic pump pressure forces. This type of model is great for modelling global behaviour on a large scale and is shown to be able to predict density wave amplification as witnessed in the Freiberg flow loop. Further uses for such a model is the designing control feedback algorithms to maintain flow assurance and dynamic drive load quantification to aid in the design of DF, SI and fuel cell drives. This model will be developed further as part of future research.
FIGURE 10
IADC's Secretary General René Koilman presents the Young Author Award 2021 to Edwin de Hoog for the co-authoring of the research paper, The relevance of time domain effects for the design and stability of hydraulic transport pipelines. The award is presented at industry-leading conferences, with last year’s winning author selected from the proceedings of the CEDA Dredging Days, held virtually 28-29 September 2021.
Summary

Traditionally, the design of a hydraulic transport system entails analysing energy sinks and sources of a pipeline system. More specifically, the energy characteristics of the pump and drivetrain are weighted against the frictional energy losses of the slurry in the pipeline. The existence and effect of density wave amplification is familiar to the dredging industry, but the exact cause and working mechanism causing amplification are still under debate. Recent research into vertical hydraulic transport for deep-sea mining has shown that density waves can occur at mixture velocities far exceeding the critical velocity (the industry standard for the minimum safety velocity above which flow is assured). Therefore, this topic is revisited in this article and new 1D CFD techniques are explored with the aim to predict density wave amplification. This article introduces the research and presents a possible 1D CFD model framework to achieve this goal. Preliminary results show that the 1D Driftflux model is indeed capable of modelling density wave amplification. Furthermore, this article provides an outlook of additional applications of 1D Driftflux modelling for hydraulic transport pipelines. Additional application include feedback controller design and aiding in dual fuel drive design.

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Edwin is a research and development engineer at Royal IHC and a part-time PhD candidate at the department of Dredging Engineering at Delft University of Technology, in the Netherlands. He is specialised in hydraulic transport of sand, gravel and manganese nodules. As part of his PhD research, Edwin is developing 1D CFD technology to simulate pump-pipeline systems and the effect of density wave amplification, applicable for long pipelines and deep-sea mining.

Arno Talmon

Arno is assistant professor of Dredging Engineering at Delft University of Technology, in the Netherlands and lectures in hydraulic transport and rheology of slurries. He is also a senior researcher/adviser at the Ecology and Sediment Dynamics Department of Deltares with 35 years of experience. Key qualifications relate to dredging, sediment dynamics, rheology, slurries in mechanised tunneling, slurries in mining and hydraulic transport. Experimental research into these subjects has led to many new findings.

Cees van Rhee

Since 1985, Cees has been engaged in research for the dredging industry. First at WL Delft Hydraulics (now Deltares) and then from 1990-2011 at Van Oord. He obtained his PhD at the end of 2002 and since October 2007 he is professor of Dredging Engineering at Delft University of Technology, in the Netherlands. His scientific achievements are modelling of highly concentrated sediment water flows and high velocity erosion of granular sediments.
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