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FLUID PRESSURE TRANSIENTS WITH AIR ENTRAINMENT

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ABSTRACT

A numerical model and computational procedure has been developed here to better compute the fluid pressure transient with air content in the pipeline of a pumping system by including the effects of air compression and gas evolution characteristics of the transported fluid. Free and dissolved gases in the fluid, and cavitation at vapour pressure are modelled.

INTRODUCTION

Pressure surge analysis is usually based on the assumption of no air in the water. however, in some pumping installations such as the sewage pumping stations, air entrainment into the system can occur due to: the falling jets of sewage from the comminutors into the sump near the operating pump bellmouths; the attached vortex formation arising from the operation of the pumps; and the adverse flow path towards the operating pumps. Air may also be admitted into the pipeline due to vortex action at an inadequately designed air vessel. Trapped air pockets at the top of pipe cross-section at high points along the pipe profile can also be presented due to the incomplete removal of air during commissioning and filling-up operation or progressive upward migration of pocket of air.Flow in the pipelines would also contain free gas, although the volumetric proportion may be small.and most liquid also contains dissolved gases in solution. Gas bubbles will be evolved from the liquid during the passage of low pressure transients. When the liquid is subject to high transient pressures, the free gas will be compressed and some may be issolved. The process is highly time and pressure dependent. The resulting pressure transients with air entrainment and gas release are considerably different from that computed according to the no air and constant friction factor models.

AIR ENTRAINMENT AND VARIABLE WAVE SPEED MODEL

Earlier investigations by Pearsall (1965/66) showed that the presence of undissolved gas bubbles in a fluid greatly reduces the wave speed. The effect of free air on wave speed is more significant under low-pressure conditions, where the volume of the free air is higher. The variable wave speed model proposed assumes the presence of free entrained air content ε_o and dissolved gas content ε_g in the liquid at atmospheric pressure. Assumptions were made that : (i) the gas-liquid mixture is homogeneous, (ii) the free gas bubbles in the liquid follow a polytropic compression law with n = 1.2-1.3 and (iii) the pressure within the air bubbles during the transient process is in equilibrium with the local fluid pressure. When the computed local transient pressure falls below the fluid gas release pressure p_g, an instantaneous release of dissolved gas of $\alpha_{gr}\varepsilon_g$ is observed. The local pressure remains constant and is equal to the vapour pressure. When the computed transient pressure recovers to a value above the gas release pressure, the equivalent amount of gas redissolved into the liquid is observed to be $\alpha_{gd}\varepsilon_g$. Since the local pressure remains constant when the computed pressure is below the gas release pressure, the maximum air content has a limit and hence the wave speed also has a lower limit which is consistent with the data observed.

Consider a mass of liquid containing a fractional volume ε, of gas in free bubble form. It can be shown that the effective bulk modulus K_T of the gas-liquid mixture, including the pipe distensibility effect and pipe constraint condition c, is given by [Lee and Pejovic(1996)],

$$\frac{1}{K_T}=\frac{1}{K}+\frac{\varepsilon}{np}+\frac{cD}{eE} \qquad (1)$$

while the local wave speed a_i at an absolute pressure p_i and air fraction content ε_i is given by

$$a_i^k=\left[\rho_w\left(1-\varepsilon_i^k\right)\cdot\left(\frac{1}{K}+\frac{\varepsilon_i^k}{np_i^k}+\frac{cD}{eE}\right)\right]^{-1/2} \qquad (2)$$

For the variable wave speed model proposed here, the initial free air fraction ε_o and dissolved gas fraction ε_g at a reference absolute pressure p_o must be specified. The initial wave speed variation along a pipeline (i = 0, 1, ..., N) is then computed through the absolute pressure distribution along the pipeline from equation (2) at k = 0 (steady state).

The transient computation of the fraction of air content along the pipeline depends on the local pressure and local air volume and is given by

$$\varepsilon_T^{k+1}=\left(\frac{p_i^k}{p_i^{k+1}}\right)^{1/n}\varepsilon_i^k$$

$$\text{and}\quad \varepsilon_o^{k+1}=\left(\frac{p_o}{p_i^{k+1}}\right)^{1/n}\varepsilon_o\ ; \qquad (3a)$$

for $p_i^{k+1}\geq p_g$ and $\varepsilon_T^{k+1}\leq\varepsilon_o^{k+1}+\alpha_{gr}\varepsilon_g$

$$\varepsilon_i^{k+1}=\varepsilon_T^{k+1}\ ; \qquad (3b)$$

for $p_i^{k+1}\geq p_g$ and $\varepsilon_T^{k+1}>\varepsilon_o^{k+1}+\alpha_{gr}\varepsilon_g$

$$\varepsilon_i^{k+1}=\left(\frac{p_i^k}{p_i^{k+1}}\right)^{1/n}\left(\varepsilon_i^k-\alpha_{ga}\varepsilon_g\right)\ ; \qquad (3c)$$

for $p_i^{k+1}<p_g$

$$\varepsilon_i^{k+1}=\left(\frac{p_i^k}{p_g}\right)^{1/n}\left(\varepsilon_i^k+\alpha_{ga}\varepsilon_g\right)\ . \qquad (3d)$$

The above air fraction content is then substituted into equation (2) to obtain the wave speed along the pipeline for computations at the next time level. For water saturated at atmospheric pressure the gas release pressure head approaches that of the vapour pressure (i.e. 2.4m water absolute). A typical free air content in sewage at atmospheric pressure is about 0.1%; the free gas content evolved at the gas release head is about 2.0% at atmospheric pressure head. The fraction of gas absorption is $\alpha_{ga}\approx 0.3$ and the fraction of gas release is $\alpha_{gr}\approx 0.6$ [Pearsall(1965), Provoost(1976)].

DISCUSSION

A typical pipeline profile of a sewage pumping station is shown in Figure 1. Figure 2 shows the effect of air entrainment and gas release in the variable wave speed model on pressure transient at the immediate downstream of the pumping station under extreme operating conditions when compared with that using a constant wave speed model with no air content. Figure 3 further shows that gas release and entrained air may increased the maximum pressure upsurge along the pipeline. A study of the many corresponding numerical experiments using the variable wave speed model and model studies with air entrainment by Lee & Pejovic (1996) shows three distinct characteristic differences of pressure surge at unprotected pumping station following power failure and instantaneous closure of the check valve when flow reverses. (a) The first pressure peak is above that predicted by the constant wave speed model and the

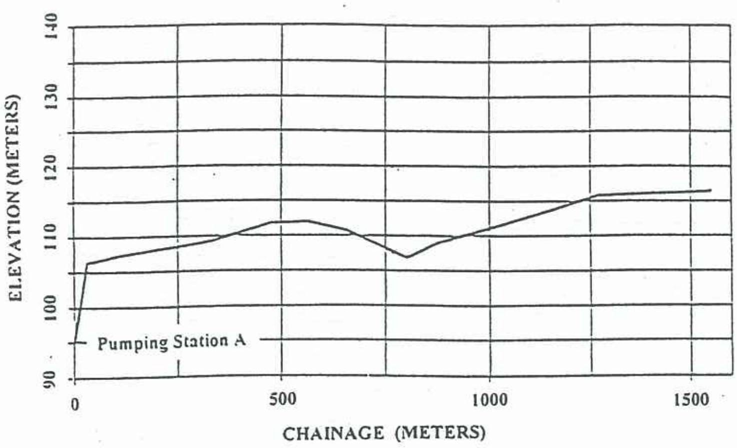

Figure 1 : Typical Profile of a Pumping Main

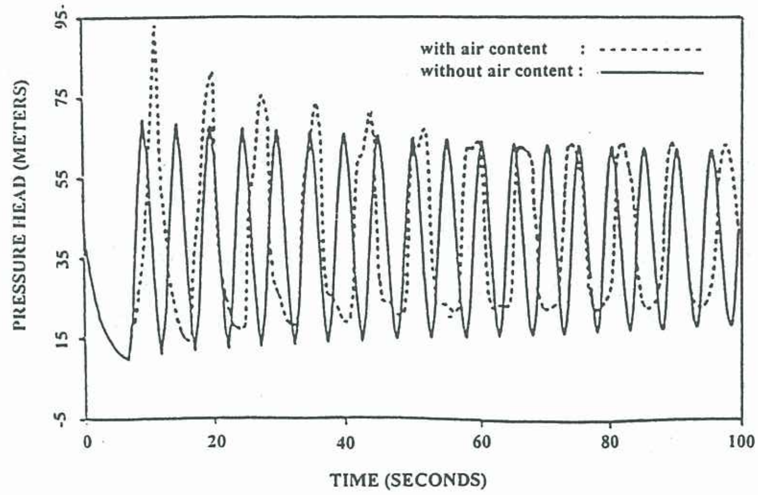

Figure 2 : Pressure Transient at Immediate Downstream of the Pumping Station

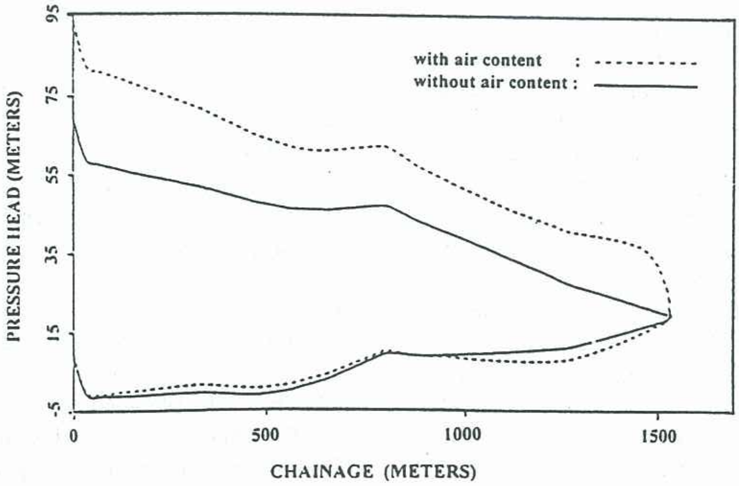

Figure 3 : Maximum and Minimum Pressure Envelope Along the Pumping Main

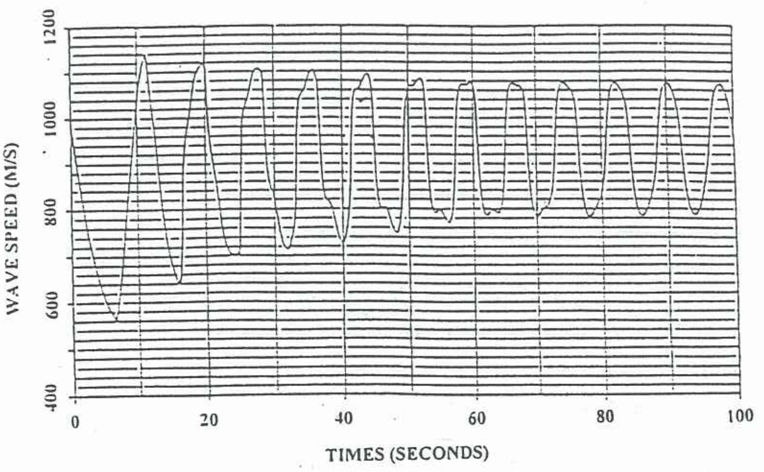

Figure 4 : Transient Wave Speed at Immediate Downstream of Pumping Station

transient time that occurs differ; (b) The damping of surge pressure is noticeably larger when compared with the constant wave speed model; (c) The surges are asymmetric with respect to the static head, while the pressure transients for the constant wave speed model was symmetric with respect to the static head. If there are evolution and subsequent absorption of the gas in the liquid along the pipeline, the initial upsurge caused by valve closure at the pumping station may be small but it very often followed by a delayed substantial pressure upsurge. This delayed substantial pressure upsurge due to gas release at the gas release head along the pipeline was also observed by Clarke(1985). The arrival of this substantial pressure upsurge at the pumping station generates a positive transient that travels upstream towards the reservoir. This positive transient raises the pressure along the pipeline and causes the free gas present in the flow to dissolve, so increasing the effective bulk modulus and thus the wave speed (Figure 4). This positive pressure wave was then reflected off the downstream reservoir as a negative pressure wave. Due to the higher pressure upstream of the reservoir, this negative pressure wave travels rapidly and arrests the high pressure upsurge at the pumping station. Hence, the substantial pressure upsurge was present for a short duration. As the surge damping due to losses and the presence of air content sets in, the pressure downsurge along the pipeline usually does not subsequently fall below the gas release head, and a regular oscillating pressure surge will then be observed. Hence, the entrainment of free air and the release of gas at the gas release head reduces the local wave speed (Figures 2 and 4) considerably and produces a complicated phenomena of reflection of pressure waves off these "cavities". The lower local wave speed also increase the duration of the pressure downsurge as compared with the duration of the pressure upsurge.

CONCLUSION

Numerical experiments showed that entrained, entrapped or released gases may amplify the pressure peak, increase surge damping and produce asymmetric pressure surges with respect to the static head.

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