Transient Behavior of HDPE Pipes due to Pressure Fluctuations

Experimental Studies: Channels

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ABSTRACT

Compared to other materials for pipelines, plastic pipelines (e.g. of PVC or HDPE) are distinguished by their flexibility and great resistance to aggressive agents. At present it can be stated that for waste water pressure lines and water supply pipelines HDPE pipes are preferred to PVC pipelines. The main reason for this is that there are no problems when HDPE pipelines are disposed.

PVC and HDPE pipelines show a viscoelastic material behaviour, i.e. deformations depend on temperature, time and pressure gradient. That means that changes in pressure and strain occurring in these pipelines of viscoelastic materials for transient flow are no more directly proportional to each other as with elastic materials, and from a strictly objective point of view, there is no more a constant speed of wave propagation. To each point of a pressure wave a definite change in cross section is attributable, which depends on the actual pressure alteration and on the preceding deformation. Detailed investigations of PVC pipelines were made with regard to periodic alterations of pressure, and, in addition, the damping behaviour of pressure waves was determined. So far, HDPE pipelines have not yet been investigated. It can be stated as well, that the HDPE deformation modulus is considerably smaller than that of PVC. Therefore, when dimensioning HDPE pipelines it is of great importance to scrutinize the effects of the viscoelastic material behaviour taking into account the supporting effect of the ground surrounding the pipeline. In this context, the occurance of quick changes in pressure and velocity are of interest in real plants, because the associated increases in pressure are decisive when pipelines and parts of plants are dimensioned. The present paper first reports on findings of pressure surge measurements made on two trenchless HDPE pipelines and of the time-dependent material behaviour, these results allowing the assessment of the influence on transient flow.

1 Introduction

PVC and HDPE pipelines show a viscoelastic material behaviour, i.e. deformations depend on temperature, time and pressure gradient. That means that changes in pressure and strain occurring in these pipelines of viscoelastic materials for transient flow are no more directly proportional to each other as with elastic materials. To each point of a pressure wave a definite change in cross section is attributable; this change depends on the actual pressure alteration. Detailed investigations of PVC pipelines were made with regard to periodic alterations of pressure, and, in addition, the damping behaviour of pressure waves was determined [1, 2, 3, 4]. So far, HDPE pipelines have not yet been investigated. It can be stated in general, that the HDPE deformation modulus is considerably smaller than that of PVC. Therefore, when dimensioning HDPE pipelines it is of great importance to scrutinize the effects of the viscoelastic material behaviour taking into account the supporting effect of the ground surrounding the pipeline.

This paper reports on measurements performed on two trenchless HDPE pipelines and on investigations on the time-dependent material behaviour of HDPE wall material. The results allow to assess the influence on transient flow in HDPE pipelines.

2 Results of measurements

To make first statements on the propagation of waves in HDPE pipelines laid in ground transient flow were measured in two trenchless pipelines of the water supply system of the cities of Halle and Oschatz, Germany. Both pipelines are water supplying pipelines between two local systems. In Halle the pipeline (HDPE 140 x 12.7) has a length of 2314 m, and the length of the pipeline (HDPE 110 x 11.8) near Oschatz was 1625 m.

For pressure measurements on both pipelines three measuring stations for each were installed distanced 650 m up to 1650 m. The expansion of the pipeline was measured on one measuring station for each. The system used here included three measuring boxes with a real-time clock, a selectable sampling frequency from 1 Hz up to 60 kHz and a storing capacity of approx. 500.000 measured values.

By repeatedly opening and closing special valves alterations of pressure and velocity were generated. The time shift between the measuring points was determined by means of characteristic points (in Figure 1a marked by arrows). Following the relation $a = \Delta L / \Delta t$ the propagation of waves with the respective lengths of lines was determined.

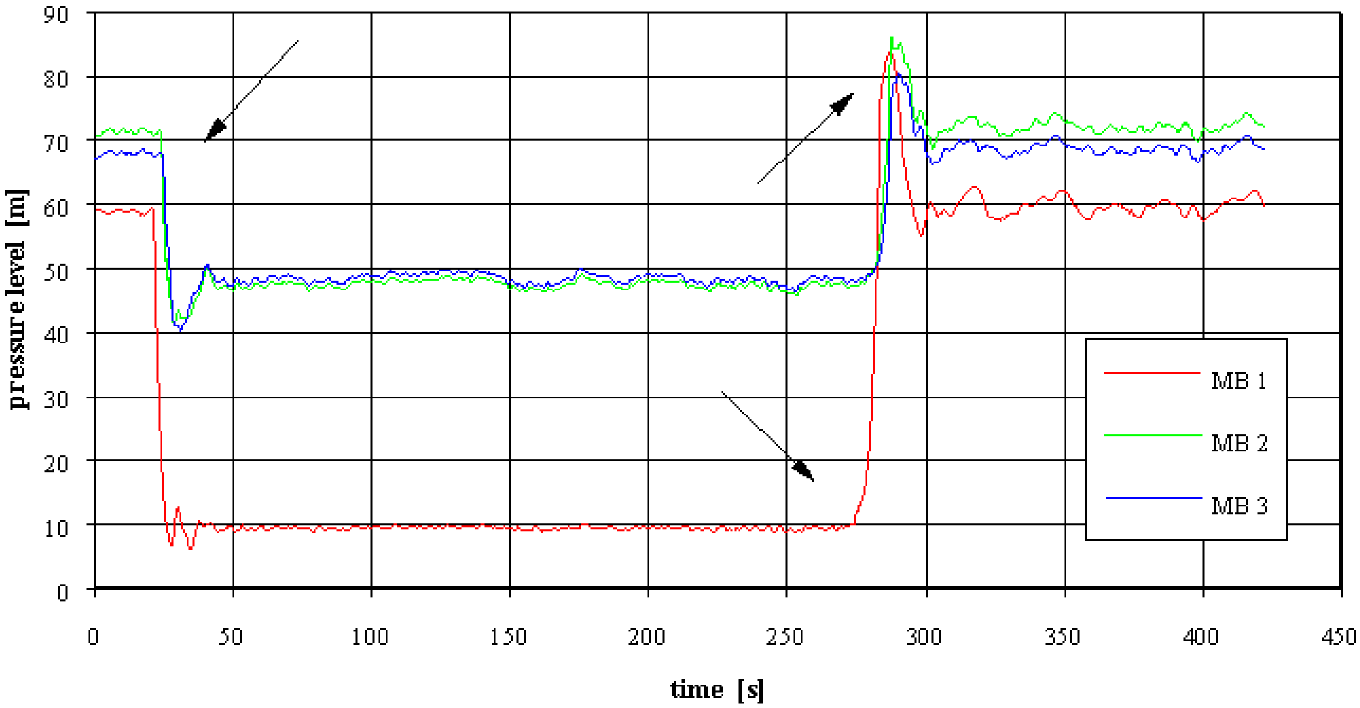


Figure 1a: Pressure variation from measurement of Oschatz

Figure 1a shows the time curve of pressure for the three measuring points of the HDPE pipeline (110 x 11.8). The wave propagation was derived from the time shift between the individual measuring stations. It was a = 541 m/s at a rate of loading of 4.5 m water head / s.

In Figure 1b, curves for pressure and radial expansion variations are plotted (on an exaggerated scale). The pressure fluctuations and the expansion of the pipe take a nearly synchronous course.

Evaluating the measurements for the radial expansion and the pressure level, an elasticity modulus of 1100 N/mm2 at a temperature of 10 °C was found. The pipeline was exposed at the measuring point and there was no active supporting effect of the ground. Under these conditions, the wave speed was 380 m/s. The stress-strain behaviour of a part of the pipeline of the same dimensions and of nearly the same rate of loading of 5.5 m WH/s was tested in the laboratory. An elasticity modulus of 1080 N/mm2 and hence a wave speed of 377 m/s were the results. Hence, it can be stated that field measurements did result in evidently higher wave speeds. Obviously, this effect can be explained by the supporting effect of the surrounding ground. This effect has to be particularly investigated.

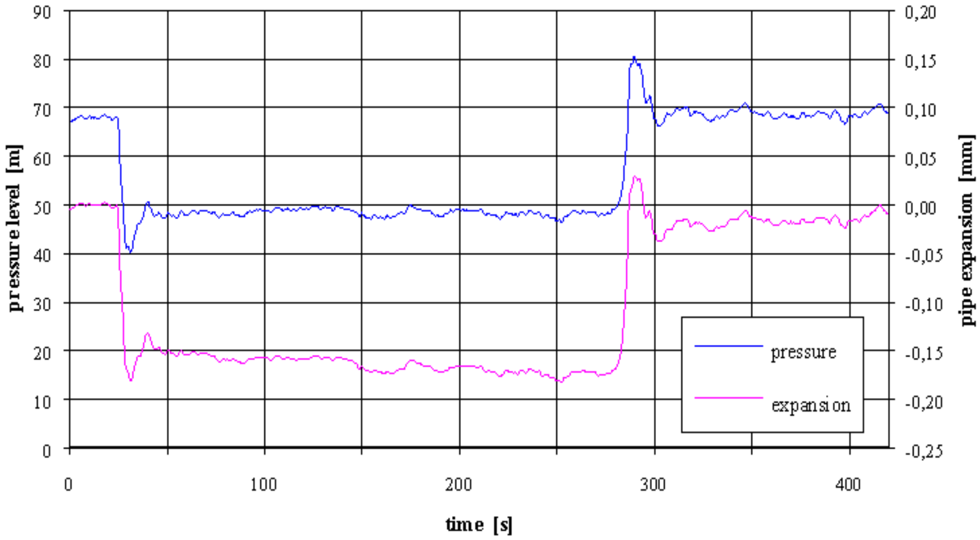


Figure 1b: Pressure and pipe expansion variation from measurement of Oschatz

In the Figures 2a and 2b a measurement for the HDPE pipeline of Halle and corresponding results were illustrated.

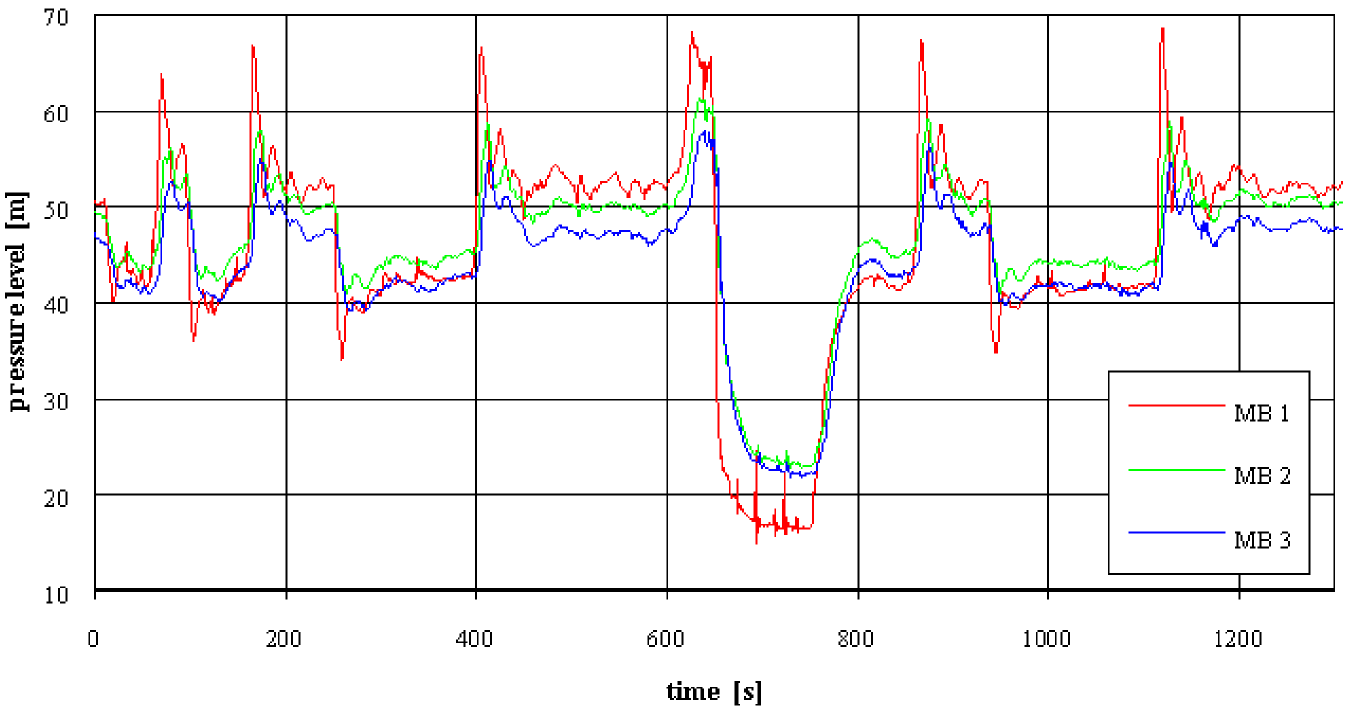


Figure 2a: Pressure variation from the measurement of Halle

It can be concluded from the tests up to now that for practical purposes at fast changes of pressure it is sufficient to expect a constant wave propagation.

For a precise description of transient flow in HDPE pipelines, however, from the scientific point of view it is essential to take into consideration the viscoelastic material behaviour, as well. In literature there is information on the long-term behaviour of HDPE, but investigations for short-time behaviour due to fast changes of load are missing. It is intended to fill the gap by the following investigations.

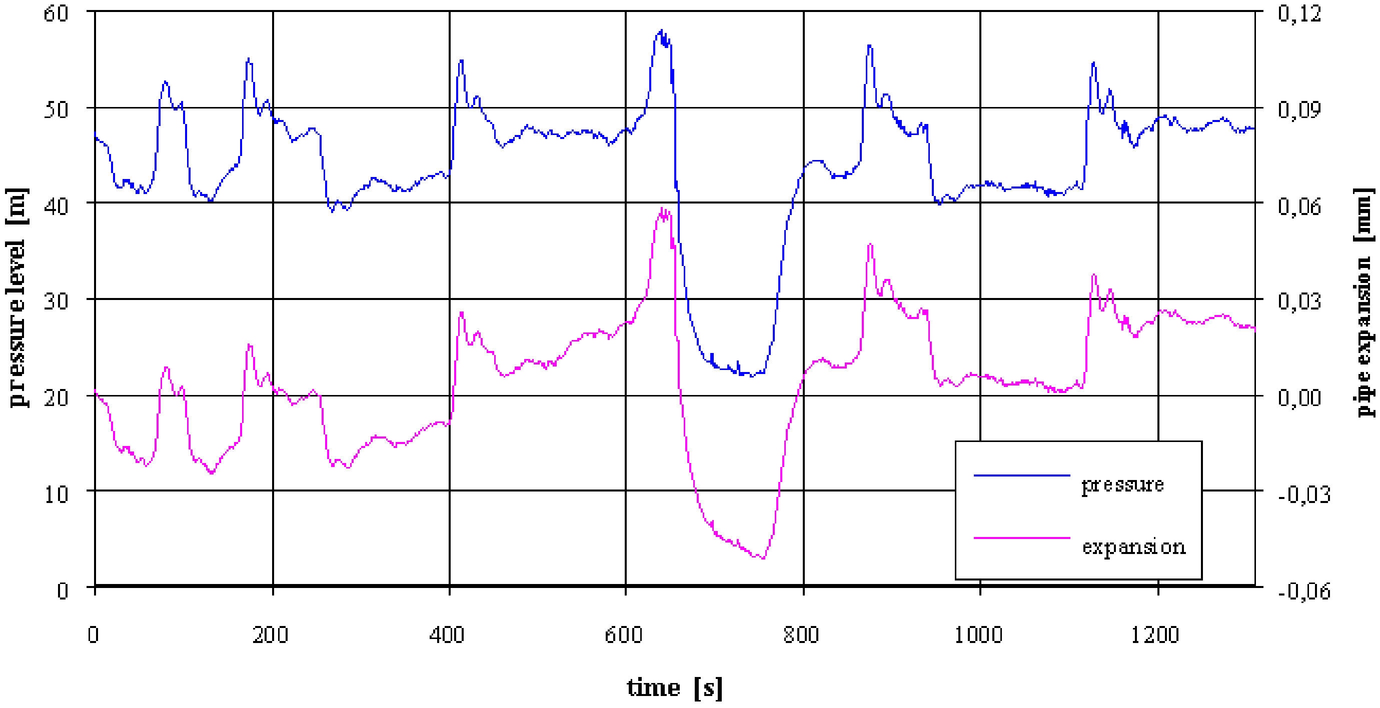


Figure 2b: Pressure and pipe expansion variation from measurement of Halle 2

3 Viscoelastic Material Behaviour

3.1 Investigation of the viscoelastic strain behaviour at load changes

Measurements of pipe expansion due to fast changes of pressure in a part of the pipeline were carried out in order to get knowledge on the time-dependent material behaviour.

The test set up (s. Figure 3) for these measurements allows to apply defined load increments by means of a precision pressure balance (dead weight tester), the internal pressure in the pipe being measured with a pressure transducer. The pipe expansion is determined through eight inductive displacement pick-ups which are arranged radially on the pipe periphery. The measured values are recorded and evaluated with the aid of a PC.

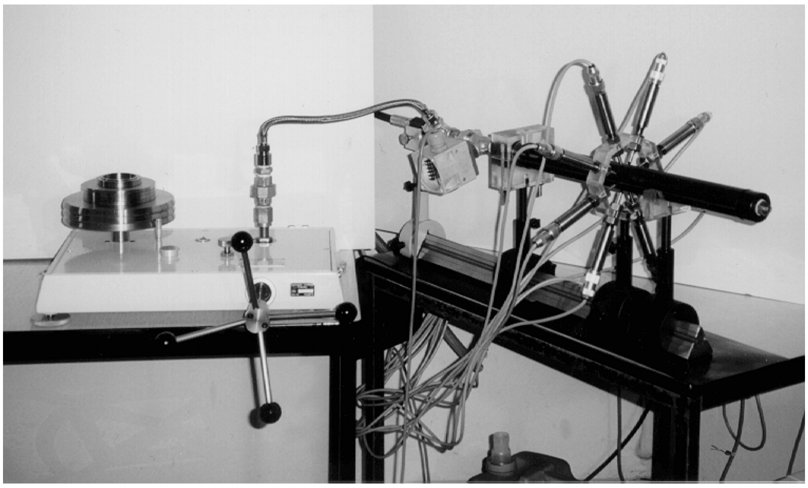


Figure 3: The test rig for investigating the stress-deformation behaviour of HDPE pipe

In Figure 4 one sees the time curve of the radial expansion in a part of the pipe
(HDPE 40 x 3.7) at a sudden increase of pressure up to 100 m WH and at a pressure reduction by 100 m WH. Two ranges of deformation can be clearly distinguished here: the deformation of the pipe during the change of pressure and the deformation at a constant pressure level. It can be clearly discerned that pressure and pipe expansion run almost synchronously. In the second range the pipe is deformed

further at a constant pressure level (viscoelastic material behaviour). It can also be seen in the figure that during this transient loading cycle almost no plastic deformation occurs.

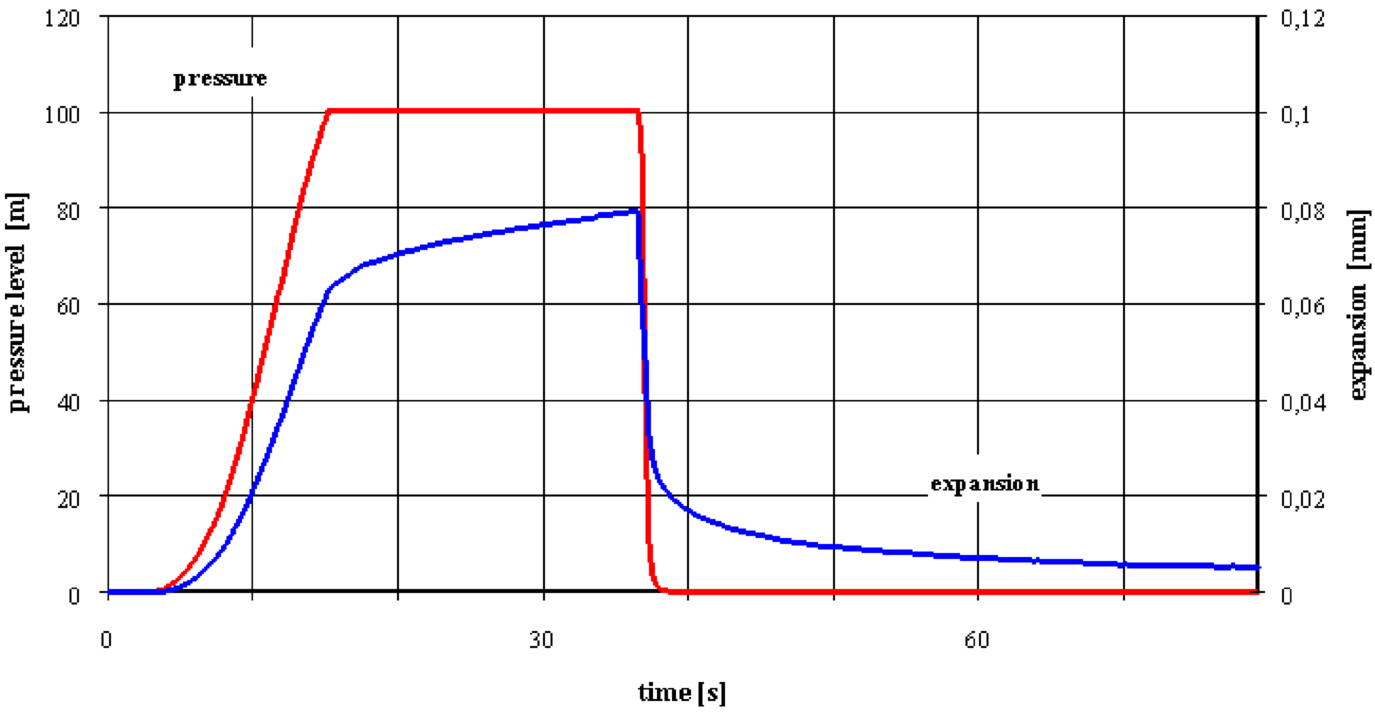


Figure 4: Time curve of pressure and pipe expansion (T = 23 °C)

For rapid pressure changes especially the first (elastic) range of the radial deformation is of interest. The stress-deformation relations can be derived approximately with the relationships

$$\varepsilon_a = \frac{w}{r_a} \quad \text{und} \quad \sigma_a = \frac{2 \cdot p_i \cdot r_i^2}{r_a^2 - r_i^2} \quad . (1)$$

In the above equations ri and ra are the internal and external radius of pipe, w is the radial expansion of pipe, ε_a is the elongation of the outer circumference, pi is the internal pressure, and a is the tangential stress at the outer circumference.

With the aid of the / diagram represented in Figure 5 one can now derive a modulus of elasticity for the deformation zone during the change of load. The slope of the mentioned ranges can be considered to be the elasticity modulus of the pipe material.

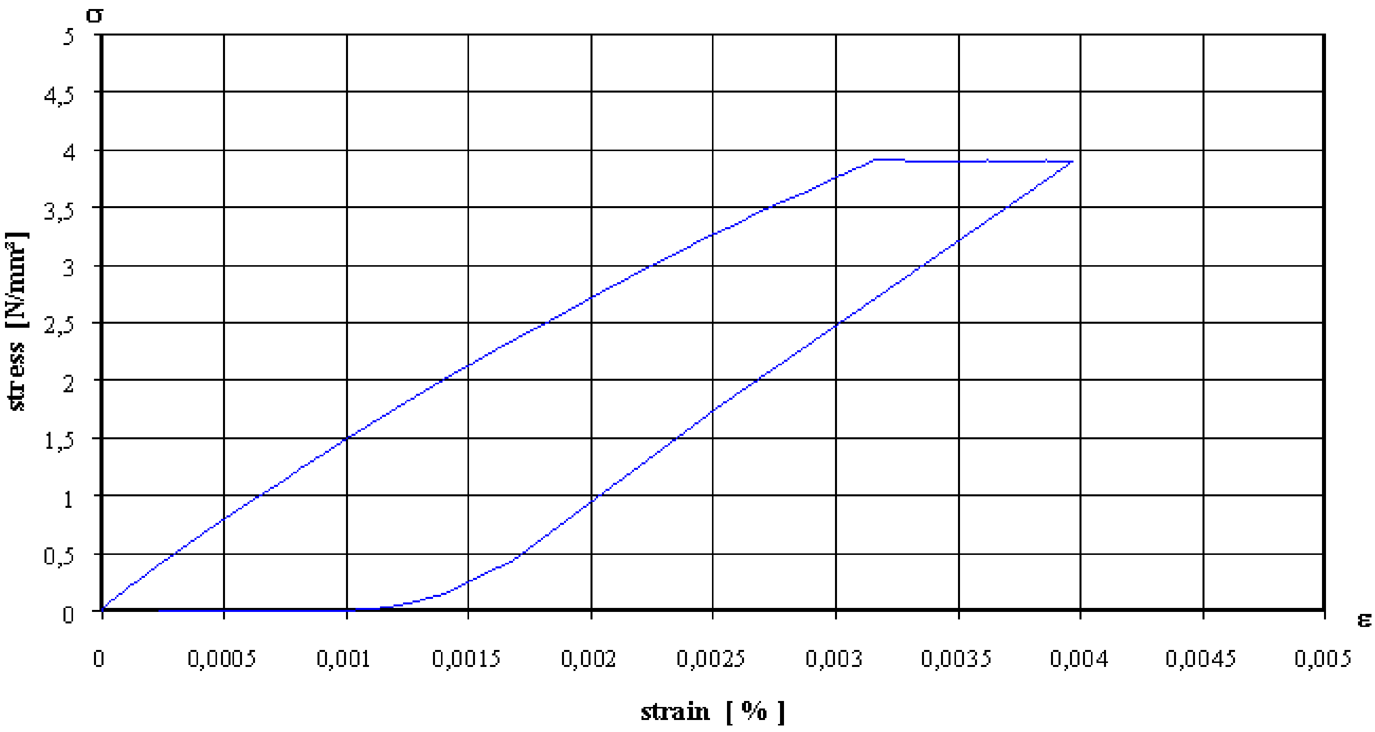


Figure 5: Stress-strain diagram for an HDPE pipeline (T = 23 °C)

In order to check the results, an approximately 90 m long surge test rig was set up in the Hubert Engels Lab of the Institute for Hydraulic Engineering and Hydromechanics at the Technical University of Dresden to measure the wave propagation. In Table 1 some results of these measurements are given.

		T = 10°C	**T = 23°C**
wave speed	**a [m/s]**	420	390
Modulus of elasticity	**E [N/mm²]**	1530	1300
Pressure gradient	**dh/dt [mWS/s]**	100	100

Table 1: Results form measurements of the pressure surge test rig

The wave speed was determined as described before from the time shift between several measuring points; with these speeds the modulus of elasticity was calculated. A comparison of the measured values at 10 °C and 23 °C illustrates the influence of temperature on the strength of the pipe material and, consequently, on the wave propagation. The correctness of the values derived from the stress-deformation relationship for the modulus of elasticity of HDPE pipelines was confirmed by the results from the pressure surge tests.

Accordingly, tests with loading rates of 5 ... 220 m WH/s were carried out. In Figure 6 the moduli of elasticity determined for this pressure gradient and the wave speeds resulting from them are plotted. Similar results were obtained in the pressure relief tests.

It was found that the elasticity modulus of approx. 1100 N/mm² at a gradient of 10 m WH/s increases to approx. 1500 N/mm² (at 220 m WH/s). The wave speeds occurring at these elasticity moduli lie in a relatively narrow range of 370 ... 420 m/s.

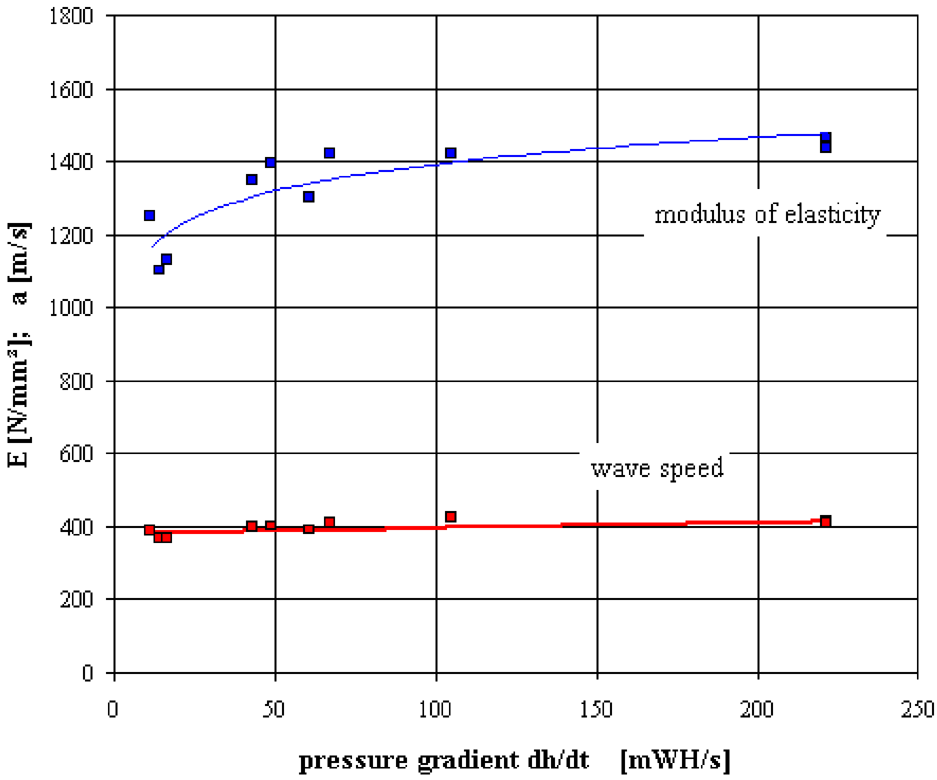
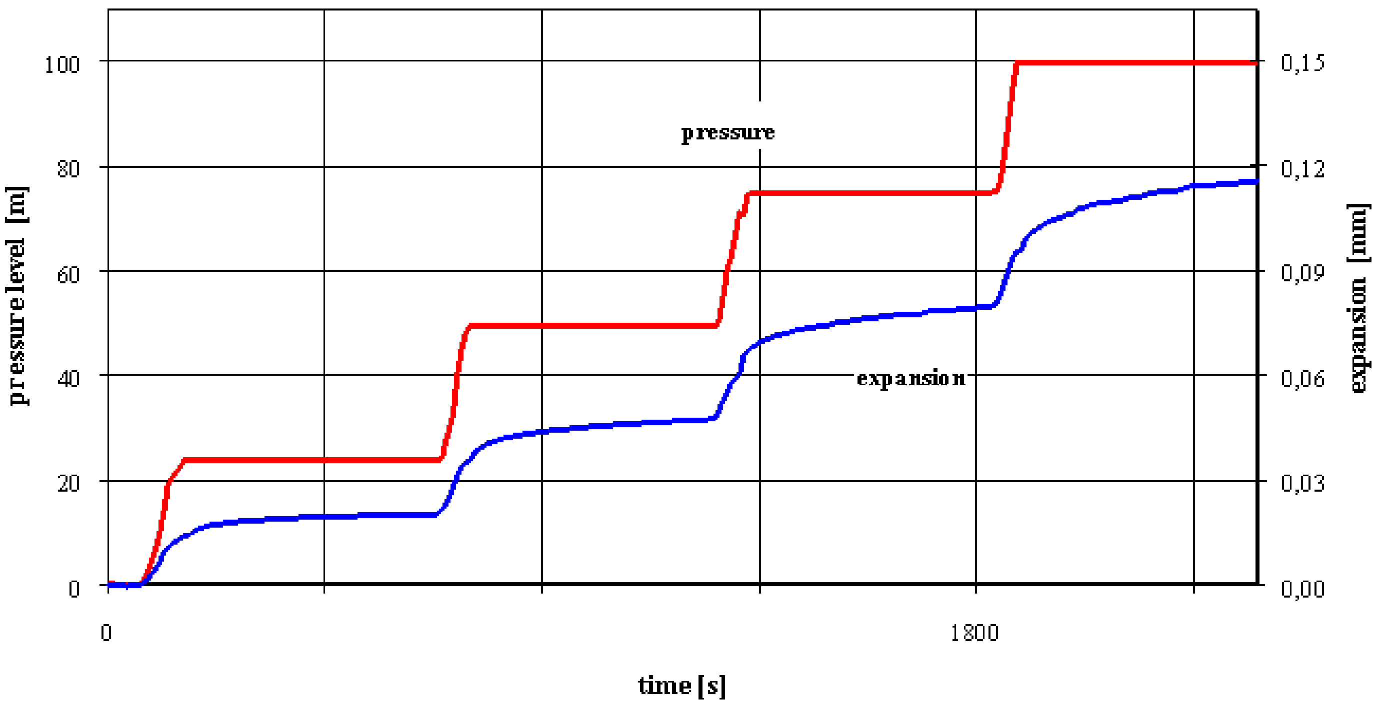


Figure 6: Modulus of elasticity at increasing load in dependence on the rate of loading (pipeline HDPE 40 x 3.7)

In order to investigate the effects of the preliminary loading, measurements were carried out at load increments. In Figure 7 the time curve of pressure and pipe expansion as well as the / diagram of such a test are represented. The modulus of elasticity is quite constant in the region of pressure changes and therefore independent of the preliminary load.



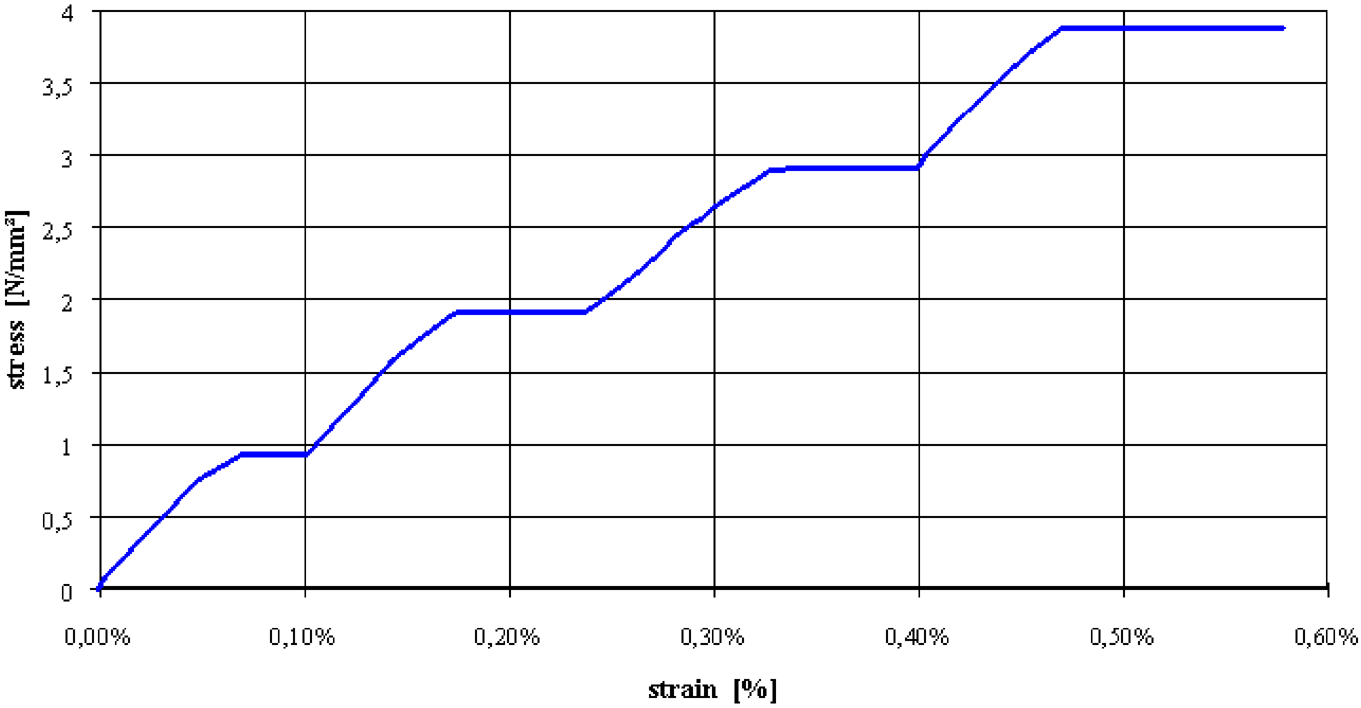


Figure 7: Measurement result of a test with stepwise loading of the part of the pipeline

The evaluation of this measurement yielded the following values for the modulus of elasticity shown in Table 2.

	Elasticity modulus **N/mm*2**	**wave speed** **m/s**
1st step (0 ... 25 mWH)	1350	397
2nd step (25... 25 mWH)	1322	393
3rd step (50 ... 75 mWH)	1383	401
4th step (75 ... 100 WH)	1361	398

Table 2: Modulus of elasticity and wave speed at stepwise loading

The laboratory investigations of the stress-deformation behaviour of HDPE pipes during rapid changes of load confirm the evaluation of the field measurements according to which a constant wave propagation can be used to assess pressure surge in HDPE pipes. The results derived by this assumption can be considered as reasonable and conservative. The accurate desciption of transient flow in viscoelastic pipes can be developed by integrating the time-dependent wall material behaviour into the basic equation of transient flow in pipes.

3.2 Basic Equations for Transient Flow in Viscoelastic Pipes

The viscoelastic strain behaviour can be described by aid of a combination of spring and damper according to a Voigt-Kelvin element and an elastic (time-independent) component [5]

$$\varepsilon(t) = \frac{\sigma}{E_0} + \frac{\sigma}{E} \cdot \left(1 - e^{-t/\tau}\right) \qquad (2)$$

where

ε = elongation of internal circumference

σ = stress

t = time

τ = retardation time of Kelvin-Voigt element

It is not generally possible to describe the viscoelastic material behaviour represented above by means of a simple Voigt-Kelvin model; this can be satisfactorily done by a simple series-connection of individual elements.

$$\varepsilon(t) = \frac{\sigma}{E_0} + \sum_{j=1}^{n} \frac{\sigma}{E_j}\left(1 - e^{-t/\tau_j}\right) \quad (3)$$

or

$$\varphi(t) = \frac{\varepsilon(t)}{\sigma} = \frac{1}{E_0} + \sum_{j=1}^{n} \frac{1}{E_j}\left(1 - e^{-t/\tau_j}\right) \quad (4)$$

where E_j = modulus of spring of the j-th Kelvin-Voigt element

τ_j = retardation time of the j-th Kelvin-Voigt element

φ (t) is designated as a creep function. Therefore, the creep function therefore can be considered to be the pipe strain for the unit stress.

This information can be inserted into the equations describing transient flow in pipes. The basic differential equations for transient flow in circular conduits are the motion and continuity equation [6,7,8].

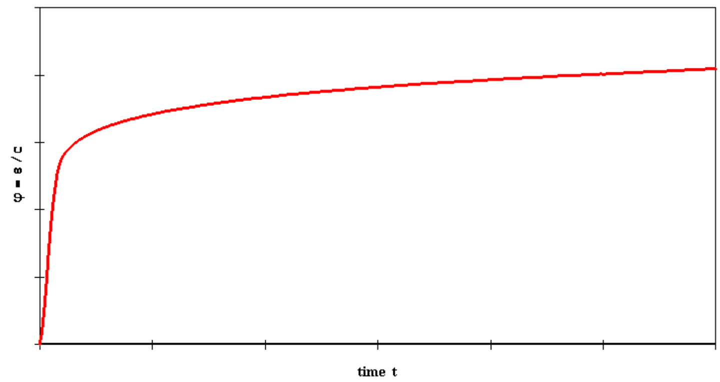


Figure 8: Creep function φ (t) recorded on a part of a pipeline HDPE 40 x 3.7

$$\frac{p_x}{\rho} + v v_x + v_t + g \cdot \sin\alpha + \frac{\lambda \cdot v|v|}{2 \cdot d} = 0 \quad (5)$$

and

$$(\rho \cdot A)_t + (v \cdot \rho \cdot A)_x = 0 \quad (6)$$

where p = pressure

v = velocity

g = acceleration of gravity

x = of pipe cordinate distance along the x-axis

α = angle of pipe (+ when elevation increases in x direction)

A = cross-sectional area of pipe

ρ = mass density of fluid

The subscripts x, t, p, ε are partial differentiation with respect to x, t, p, ε

We define

$$d_\varepsilon = \frac{dv}{r} \quad (7)$$

$$\frac{dA}{d\varepsilon} = 2A \quad (8)$$

and $$\frac{d\rho}{dp} = \frac{\rho}{E_W} \quad (9)$$

where r = radius of pipe

E_W = bulk moduls of elasticity of fluid

The continuity equation (6) can be expanded to

$$\rho A_\varepsilon \cdot \varepsilon_t + A\rho_p p_t + \rho A v_x + \rho v A_\varepsilon \cdot \varepsilon_x + vA\rho_p p_x = 0 \quad (10)$$

With equations (8 and 9) equation (10) can be written

$$p_t + vp_x + 2E_W(\varepsilon_t + v\varepsilon_x) + E_W v_x = 0 \quad (11)$$

Assuming a viscoelastic behaviour of the pipe wall behaviour according to (3), we can write

$$\varepsilon = \varepsilon_0 + \varepsilon^* = \beta\frac{p_0 r}{E_0 s} + \sum_{j=1}^{n}\frac{p_j \cdot r}{E_j \cdot s}\left(\beta - e^{-\frac{t}{\tau_j}}\right) \quad (12)$$

with $$\beta = (1+\mu)\frac{s}{r} + (1-\mu^2)\frac{(2r)}{(2r+s)} \quad (13)$$

where β = factor for thiek-walled pipe, anchored against longitudinal

movement [6]

μ = Poisson’s modulus

s = pipe wall thickness

Substituting (12) in (11) we finally get

$$p_t + v\rho_x + \rho c^2 v_x + 2\rho c^2(\varepsilon_t^* + v\varepsilon_x^*) = 0 \quad (14)$$

where
$$c^2 = \frac{E_W/\rho}{1+\frac{\beta \cdot E_W \cdot r}{E_0 \cdot s}} \quad (15)$$

We assume the simplification v < c and n = 1 (one Kelvin-Voigt) Element. (5) and (14) can be transformed into ordinary differential equation applying the method of characteristics.

$$\frac{dp}{dt} \pm \rho \cdot c \frac{dv}{dt} + \frac{2 \cdot \rho \cdot c^2}{\tau_1}\left(\beta \frac{r \cdot p}{E_1 \cdot s} - \varepsilon_1^*\right) + \frac{\lambda \cdot v|v|}{2 \cdot d} = 0 \quad (16)$$

and
$$\frac{d\varepsilon_1^*}{dt} - \frac{1}{\tau_1}\left(\beta \frac{r \cdot p}{E_1 \cdot s} - \varepsilon_1^*\right) = 0 \quad (17)$$

in which (16) are the so-called compatibility equations which are valid along the two characteristic lines $\frac{dx}{dt} = \pm c$ and (17) is valid along $dx/dt = 0$. The equations can easily extended to case for n > 1.

$$\frac{dp}{dt} \pm \rho \cdot c \frac{dv}{dt} + \sum_{j=1}^{n} \frac{2 \cdot \rho \cdot c^2}{\tau_j}\left(\beta \frac{r \cdot p}{E_j \cdot s} - \varepsilon_j^*\right) + \frac{\lambda \cdot v|v|}{2 \cdot d} = 0 \quad (18)$$

and
$$\frac{d\varepsilon_j^*}{dt} - \frac{1}{\tau_j}\left(\beta \frac{r \cdot p}{E_j \cdot s} - \varepsilon_j^*\right) = 0$$
, j=1...n (19)

It can be seen that the programing of the equation above including boundary conditions are similar to pipe consisting of wall material with elastic behaviour.

At the moment, extensive investigation are being made to include the behaviour of the ground surrounding the pipe. The investigation have not yet been completed.

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