(54) Title: LEAK LOCATION

(57) Abstract

When an underground pipe carrying a fluid, such as a buried water–pipe, develops a leak the leak must first be located before it can be repaired. One common location method makes use of the fact that the leaking fluid often creates a noise, typically a hissing sound, which is transmitted through the ground, and although rapidly attenuated can be heard with suitable highly sensitive ground microphones and is therefore useful to field crews as a means of locating leaks. Unfortunately, the sound levels can be grossly distorted by underground heterogenities, and can easily be confused or even swamped by other sound sources above ground, and in general ground microphones used like this do not seem to be effective. The invention deals with the problems entailed in this technique by a method – and apparatus – which involves using semi–automated equipment to listen (either simultaneously or sequentially) to the leak sound source (1) from a multiplicity of different positions (as 3) spaced all around the sound source, and by then suitably combining and processing the received signals to provide the desired indication of the source's location.

Leak location

This invention is concerned with leak location, and
relates in particular to the determination of the
location of a leak of fluid in an underground pipe. It
has regard especially to leak location by means of a
surface detector array which detects ground motion.

There are many situations in which an underground
pipe carrying a fluid - a gas or a liquid - develops a
leak, which leak must then be located and repaired. A
good example is the case of water distribution pipes
buried at a depth down to a few metres below ground.
One common location method makes use of the fact that
the leaking fluid often creates a noise, typically a
hissing sound, which is conducted along the pipe as
vibration. The sound is also transmitted through the
ground. Although the sound is rapidly attenuated by the
ground, it is possible to hear the sound with suitable
highly sensitive ground microphones, and therefore
ground microphones are often made available to field
crews in the water industry as a means of identifying
and locating leaks.

It is naturally desirable to locate the leak simply
by listening to the sound at the ground surface. Crews
do sometimes try to use a ground microphone for final
fixing of the position of a leak by moving the
microphone around and searching for the point at which
the leak noise is loudest. Unfortunately, the sound
levels can be grossly distorted by underground
heterogenities, and can easily be confused or even
swamped by other sound sources above ground. · In

- 2 -

general, then, ground microphones do not seem to be
effective, mainly because background noise obscures the
signal, and this has reduced their credibility with
field crews. The invention deals with these types of
problems encountered by water leak location teams by
listening to the leak sound source from a multiplicity
of different positions spaced all around the sound -
listening either simultaneously or sequentially - and by
then suitably combining and processing the received
signals to provide the desired indication of the
source's location.

    In one aspect, therefore, the invention provides a
method of determining the location of a leak in an
underground pipe carrying a fluid, in which method the
movement of the ground caused by the fluid as it leaks
from the pipe is listened to using sensors at a
multiplicity of positions spaced over the ground surface
and disposed within an area extending over the suspected
location of the leak, and by suitably combining and
operating upon the signal information received at each
position there is determined the actual location of the
leak.

    The invention concerns determining the location of
a leak in an underground pipe carrying a fluid. The
pipe may be of any sort - that is, made of any
appropriate material and of any size - and the fluid may
likewise be of any sort, gas or liquid. The invention
is, however, of particular use in connection with water-
bearing pipes.

    Underground water-bearing pipes can be of a wide
variety of diameters ranging from a few centimetres (for

- 3 -

local distribution to domestic property) to more than a
metre (for mains service pipes). The depth of burial
can also vary from the order of half a metre down to
several metres.

The type of ground in which the pipe is buried
varies a great deal in terms of its homogeneity, its
stiffness and the top cover. For example, the
surrounding ground may be a roadbed, in which case it
will be well consolidated, and propagates sound well.
It could equally well be a field or grass verge, which
is less well consolidated and so sound travelling
therethrough propagates less well. Moreover, the actual
top surface may be one or more of several materials,
typically concrete, tarmacadam or soft earth.

The material of the pipe is likely to depend upon
both the application and the age of the pipe. Common
materials encountered are cast iron, ductile iron, high
or medium density polyethylene, and UPVC (ultraviolet-
stabilised polyvinyl chloride). The wall thickness of
the pipe is likely to vary (with the material and the
application) from a few millimetres upwards over a range
factor of the order of five - thus to perhaps
25 millimetres and more.

Depending on the pipe's purpose, the pressure
within the pipe can range from little more than
atmospheric pressure to several Bars. Any such pipe can
develop a fault which results in a leak. The fault can
be a small diameter hole, a circumferential crack, a
longitudinal crack, or a fault at a joint from which the
pipe's contents can seep slowly or rapidly depending
upon the size of the fault. Very slow seeping leaks
which can occur at poorly fitting joints are not likely
to generate sufficient leak noise to be heard at the
surface of the ground. Other leaks are known to

generate noise at the leak which propagates along the
pipe wall, and through the fluid in the pipe, through
the ground around the pipe, and through any combination
of these paths.

A pool of fluid-saturated ground may develop around
the leak. There may be a washed out volume around the
leak, so that the leak flows directly into the pool
rather than directly into the ground.

The pipe material, wall thickness, diameter, ground
condition and nature of the leak will all influence the
magnitude, the frequency range and frequency spectrum of
the leak noise generated, but will not prevent the leak
noise occurring. The magnitude of the ground motion
will attenuate rapidly with distance from the source.
Similarly, the frequency range will fall rapidly with
distance from the leak (the rate of attenuation normally
increases with frequency, so that higher frequencies are
preferentially attenuated as distance increases). The
level of ground motion expected will be of the order of
$0.01m/s^2$, being higher or lower by an order of magnitude
or more depending on the leak, the depth of burial, the
type of ground, and the lateral distance from the leak.
Similarly, the frequency range can be expected to be up
to a few kilohertz, depending on circumstances -
sometimes it will be below one kilohertz. The motion of
the ground is liable to be predominantly vertical with
some lateral motion.

In the invention the movement of the ground caused
by the fluid as it leaks from the pipe is listened to
from a multiplicity of positions spaced over the ground
surface and disposed within an area extending over the
suspected location of the leak. The multiplicity of
positions at which the motion of the ground is measured
can consist of a number of discrete locations forming an

- 5 -

array - a geometrical array, possibly a one-dimensional
(or linear) array, but preferably a two-dimensional (or
area) array - over the area of ground. Such a system of
discrete locations involves an individual measurement
sensor sited at each discrete position, and is referred
to herein as a fixed array system. If possible, where
the array is linear, or has linear components, then the,
or one of the, lines of sensor positions should
preferably be aligned with the underground pipe being
checked.

Alternatively, the ground may be scanned by a
remote measurement system - in effect a single sensor is
moved, position by position, through and over the chosen
area so that it may listen from a large multiplicity of
positions one after the other. Indeed, the multiplicity
of positions can be so large, and the individual,
adjacent positions can be so close to each other, that
the ground motion is effectively measured as a
continuous distribution with respect to position on the
surface. A system using a sequence of positions is
referred to herein as a scanning system.

The invention uses the measured motion of the
ground surface above the leak in order to determine the
location of the leak. The method involves the detection
of ground motion over an area of ground extending over
the suspected location of the leak. Although in
principle this area could be as small or as large as
desired, most preferably the area's lateral dimensions
do not greatly exceed the depth of the pipe in which the
leak has occurred - say, not more than three times that
depth. Thus, given the range of pipe depths of zero to
two metres, the lateral dimensions of the area
investigated would be similar, at around two to at most
five metres.

- 6 -

The ground movement is listened to by sensor devices positioned at the chosen positions spaced over the leak area's ground surface. The actual detector elements forming the active portion of the sensors may be of any type able to detect motion of the ground at a point without substantially altering the ground movement. For example, they may be moving coil electrodynamic devices (which respond to velocity) or piezoelectric or piezoresistive accelerometers (which respond to acceleration). Alternatively, they may work by optical interference. Normal seismic geophones of the velocity-sensitive type are limited in upper frequency by their casing design but this is not an intrinsic limit; the intrinsic limits on the sensor are the sensitivity (it has to be able to respond to the small ground motion), the background electrical noise (the measured signal must exceed the background electrical noise in the device), and the mass (heavy sensors load the ground and modify its motion). Relatively-light weight sensors are therefore essential.

A significant problem with discrete sensors is that of the stiffness of the interface between the device and the ground. When affixed intimately to the ground the sensor device should faithfully respond to the movement of the ground. However, when simply placed on the ground and held only under gravity such devices have a resonant frequency which is dependant on the mass of the device and the stiffness of the interface between the ground and the device. The resonant frequency results in the device responding preferentially to any excitation at that frequency, and as a consequence the true magnitude and phase of the signal may be lost in the region around that frequency. Further, the exaggerated signal at the resonant frequency means that subsequent signal amplifiers may need to have their gain reduced to avoid overloading. This may result in poor

signal-to-noise ratios for signals not near the resonant
frequency.

Also, as noted hereinbefore the transmission loss
through the ground varies with frequency, which means
that the range of frequencies observed at a sensor will
depend upon the distance from the leak. With a resonant
sensing device, the measured response would not be
defined uniquely by the distance to the leak either in
phase or magnitude. Such mounting resonant frequencies
should therefore very preferably be avoided. While in
seismic applications the frequencies of interest are
low, of the order of 100 Hertz, and seismic geophones
are designed to have their first resonance above the
frequencies of interest, in the present application the
frequencies of interest can extend up to a few
kilohertz. The static weight of a 100gm sensor brings
the resonant frequency to the region of 1 kHz, which is
well within the measurement range of interest. A 10gm
device would raise the mounting resonance to the order
of 3 kHz, which is still in the measurement range.

The lower the weight of the sensor the greater the
intrinsic noise of the device. This noise limits the
lowest practical weight of a sensor for this application
to more than 10gm. The possibility of an unwanted
mounting resonance occurring within the frequency range
of interest can however be mitigated in part or even in
whole by damping the movement of the sensor, and such
damping can be provided by mounting the sensor on a mat
of some rubber-like material such that the mat presses
the sensor onto the ground.

This concept is itself both novel and inventive,
and in a second aspect the invention provides, for use
in the method of the invention, ground-motion detection
apparatus comprising a multiplicity of discrete ground-

- 8 -

motion sensors each in use contactable with the ground, together with a body of a high damping material to hold each sensor in ground contact and thereby avoid significant mounting resonance effects between the sensor and the ground.

The nature of the sensors, and the manner in which they are disposed, is discussed hereinbefore. It might be helpful, though, to add the following. There are two basic types of motion sensor that do not need an absolute frame of reference. One such type is the geophone type, as used in seismology; these respond to velocity, usually by detecting the current generated in a coil moving in a magnetic field (like a dynamo). Geophones are very sensitive, low noise devices, but typically have internal resonances below 1 kHz, which tends to limit their application to sensing low frequency motion. Another such types respond to acceleration - *changes* in velocity - and commonly work by measuring the voltage induced in a piezoelectric material supporting an accelerated mass. Accelerometers have a wide useful frequency range, high sensitivity and low noise, and as such can be suitable for use with the leak detection method of the invention.

The body of a high damping material is conveniently a mat - that is, an area-extensive sheet - that is used to hold the sensor in ground contact simply by the weight of the mat holding the sensor down. Its use enables the avoidance of significant mounting resonance effects between each sensor and the ground because it absorbs and dampens the energy transmitted into it from the ground through the sensors.

One such high damping material that provides extremely effective damping is the polymer type EAR C-1002-12 as supplied by Dowty Energy Control Products.

- 9 -

The damping mat needs to be flexible enough to conform to the contours of the ground, yet it also needs to be stiff enough to maintain the sensor in a position such that the preferred direction of motion sensitivity is at right angles to the mat. A mat of order 3 millimetres thickness of the above EAR C-1002-12 material will conform to the ground adequately.

To raise the stiffness of the mat around the sensor, a series of concentric annuli of the same material graded in increasing radii can be assembled therearound. Using concentric increasing radii of material will gradually match the stiffness of the unsupported mat to the high stiffness around the sensor without any great discontinuity in stiffness. However, it is very important that a good bond be achieved between the individual layers of mat material and with the sensor. The adhesive needs to be flexible to allow movement, and obviously must not react adversely with the mat material or the sensor itself. A suitable flexible adhesive for use with the EAR C-1002-12 material is that referred to as type A.8438/A.107 supplied by Apollo Chemicals Limited; it will bond both to the metal of the sensor and to the mat polymer.

To add weight - and to keep the signal- and power-bearing cables from damage - a second mat can be placed over the first one.

The base of the sensor can be conical - that is, be shaped to have an inverted cone whose length can be suited to the ground hardness, and used with the apex of the cone touching the ground. A lightweight spacer can be placed over the sensor to protect the cable in case an operator should use a foot to press the cone into a soft surface material. A suitable material for this spacer would be TUFNELL or even aluminium.

The MTN/1800 piezoelectric accelerometer (with
built-in amplifier) supplied by Monitran Ltd, could be a
suitable device; it has a mass of 9gm, sensitivity of
0.1volts/ms-2, with electrical noise equivalent to
0.003ms-2, and a resonant frequency of 8kHz. However,
Monitran's similar MTN/1130F is preferable, with a mass
of 30gm, sensitivity of 1.0 volts/ms-2, electrical noise
equivalent to 0.001ms-2, and a resonant frequency of
18kHz.

If several discrete sensors are used they will be
disposed as an array of sensors over the ground. There
may be one line of sensors, the individual sensors being
preferably equally spaced along the line (a suitable
spacing for the sensors would be of the order of a few
tens of centimetres), or there may be two such lines at
some angle to each other. Indeed, the preference is for
two lines orthogonal to each other.

The spatial dimensions of the array will be chosen
to ensure that sufficient resolution can be achieved
when interpreting the measured ground responses to
locate the leak. The array will typically be of the
order of a few times the depth of the pipe - thus
around 2 to 5 metres wide.

The sensors can be all scanned - that is, their
output signals read in - simultaneously. Alternatively,
even the multiplicity of sensors in a fixed array may
have its component sensors scanned sequentially. In the
latter case it is preferred to scan the sensors in
pairs, with one - usually the one at the centre of the
area - regarded as the reference, and this would always
be recorded at the same time as each of the others are
scanned. In this way there will always be at least two
sensors being recorded at the same instant.

Rather than a fixed array system, though, there may
be employed a scanned system. Thus, a non-contacting
laser motion measuring device such as the VPI sensor
manufactured by Ometron Ltd can be used to scan the area
of ground above the leak. Alternatively, the laser
motion measuring device may be replaced by a
non-contacting high frequency microwave ground motion
detector. With either the laser device or the microwave
device there is no intrinsic limit to the number of
points at which measurements can be made, so that a true
distribution of ground motion can be obtained over the
area of interest.

The lateral motion of the ground surface can be
measured in addition to the vertical motion. The
lateral motions in two orthogonal directions plus the
vertical motion will determine the vector of motion of
the ground surface. The vector of motion of ground
surface may be measured using any three non-parallel
measurement directions.

The noise from the leak can reach any sensor by a
wide variety of paths. The direct path from the leak to
the sensor through the ground is that taken by the
compressional wave known as the P-wave, and will
generally be the fastest route from the leak to the
sensor. Whenever a P-wave meets an interface, such as
the surface of the ground, it undergoes a conversion
into other types of wave - typically shear waves, known
as S-waves, plus Lamb and Rayleigh waves (which are
confined to the ground surface). There are a wide
variety of other possible paths, such as along the pipe
and then radiated into the ground, and many of these
involve reflections, diffractions and refractions at
material interfaces below the ground and at the ground
surface. The various paths have different sound speeds.

As a result of these various paths, the total
contribution of leak noise to the motion at the sensor
can be complicated. Each measurement can be compared
with one selected reference measurement, not necessarily
the centre one, and then the relative timing of the two
signals is adjusted relative to each other until the
best match is achieved. The relative time shift
required to obtain the best match is the time delay of
signals between the two stations. This process can be
achieved by the signal processing technique known as
cross-correlation. Cross-correlation has the benefit of
improving the rejection of unwanted signals that are not
present at both sensors. The cross correlations would
be averaged over several responses to improve the
signal-to-noise ratio even further. The
cross-correlations give the times of arrival of the
various waves at the sensor in question relative to the
arrival at the reference sensor.

If only the P-waves existed (with no extra
reflections), and the ground were homogeneous, then the
relative arrival times at different sensors plotted
against position across the array would reveal a portion
of a hyperboloid surface whose extremum corresponded
with the position in the array immediately above the
leak (if in fact the leak is located *beyond* the area
covered by the array then the hyperboloid will indicate
that fact since no extremum will be found, and the array
is moved to a new position ready to try again). The
hyperboloid allows not only the horizontal position of
the leak to be determined but also the wave speed of the
leak noise through the ground and the depth of the leak
below the ground surface. The presence of other wave
types and routes will corrupt the hyperboloid, but it is

still possible in principle to determine the location of
the leak from the time signals at the various sensors.

There will be occasions when the cross-correlation
process does not work. For example, if the leak noise
frequency spectrum is not broad band but rather has some
distinct frequency bands then deduction of relative
arrival times from cross-correlations will be
impossible. Also, if there are a large number of
reflecting and refracting interfaces underground then
the measured signals will have very confused frequency
spectra which will make the interpretation of
cross-correlations impossible. This situation may
sometimes be exacerbated by the dispersion of ground
surface waves, their speed of travel depending upon the
frequency. Phase information would be lost by the
transmission process. In such circumstances it is still
possible to use other methods to interpret the signals:-

The ground will attenuate signal power at least
as the square of the inverse of the distance
travelled. Location of the point of greatest
signal power along the array will give a good
indication of leak location.

The ground will attenuate high frequencies faster
than low frequencies. The loss of high frequency
energy with distance away from the leak can be used
to infer the position of the leak.

There are various means that can be used to process
the data to improve resolution of the leak location:-

If the full vector of ground movement has been
measured rather than just the vertical movement
then these additional measurements can be used to
assist in separating the different wave types to

- 14 -

reduce corruption of the hyperboloid in
time-distance space.

In some situations it will be useful to utilise
filtering in the frequency-wave number space to
assist in filtering the data to improve results
(frequency-wave number space results from a two
dimensional Fourier transform of time-distance
data).

A mathematical model of the underground
conditions can be postulated, and by an inversion
procedure the unknowns in the model can be derived.
Possible unknowns include leak location, ground
attenuation, wave speed in the ground, and the
location of any reflecting surfaces.

If the cross-correlation method fails then
analysis involves examination of the attenuation of
magnitude with distance from the leak and the
increasing attenuation of high frequency energy
with distance from the leak. A simple mathematical
model of the attenuation of magnitude and frequency
with distance can be postulated and inverted to
improve leak location, leak depth and leak noise
spectrum. The inversion process may be carried out
for each of the two lines of geophones separately.
This is simpler to perform and has the added
benefit of allowing for different combinations of
wave types in the two lines. Even if it turns out
that the leak does not lie directly under the
array, then as long as signal levels are great
enough to be detected, the analysis will point
which way the array should be moved in order to lie
over the leak. It will be best then to move the
array as indicated, and repeat the measurements,

- 15 -

rather than to extrapolate outside the array for
the leak location.

A distribution of ground motion is typically
measured in the geophysics exploration seismology
industry by means of a seismic array of vibration
sensors to gain information about the structure of the
earth up to several kilometres below its surface. In
seismic exploration the source of vibration is
deliberately introduced by one means or another -
usually an explosion - and the source is measured. The
objective is to detect reflecting surfaces within the
earth. At great depth the heavy attenuation imposed by
passing the produced noise signal through the ground
limits the seismic applications to low frequencies, but
at low frequencies the spatial resolution is poor. In
comparison with the seismic situation, leaks in water
pipes occur at shallow depths of a few metres as opposed
to a few kilometres; the source of the leak vibration
lies at the buried object to which there is no easy
access and the vibration signal of the source is
unpredictable, whereas in a seismic situation the
vibration is deliberately introduced; and for leak
detection the objective is to locate the vibrating
source and determine its acoustic power spectrum rather
than to identify reflecting geological features within
the earth as is required in seismology.

The noise issued by the leak may be broadband
random noise up to several kilohertz in frequency but
the frequency spectrum may be shaped by the physical
process involving the leak. At shallow depths such high
frequencies can survive the heavy attenuation imposed by
passing through the ground. The use of high frequencies

- 16 -

provides a good spatial resolution that is not
obtainable in conventional seismic surveys.

An embodiment of the invention is now described,
though by way of illustration only, with reference to
the accompanying diagrammatic Drawings in which:

Figure 1   shows shows a plan view of the
            accelerometer array laid out on the
            surface of the ground in relation to
            some possible position of an underground
            pipe with a leak;

Figure 2   shows a side view of the same layout as
            Figure 1; and

Figure 3   shows some of the possible paths of
            noise from the leak to the array.

Figure 4   shows detail of the mat which supports
            the accelerometer.

The embodiment of the invention shown in
Figures 1-3 involves the use of discrete measurement
sensors deployed as an array forming two orthogonal
lines. The apparatus is an array (11) of sensitive
accelerometers (as 3) connected by a robust connecting
cable (4) and linked to a data collection system (not
shown) by means of a data cable (5). The array 11 of
accelerometers 3 is deployed on the surface of the
ground (9: Figure 2) so as to detect the location of a
leak (1) in a pipe underground (2; shown in dashed
outline). The accelerometers 3 are vibration-detecting
devices which are specified to work up to high
frequencies to measure the vertical motion of the ground
surface 9. The array 11 has discrete equally-spaced
sensitive accelerometers 3 on two lines at right angles

to each other. The accelerometers 3 shown here are
measuring the vertical motion of the ground surface.

Noise from the leak 1 may propagate to any one
accelerometer 3 by a number of paths, some of which - 6,
7 and 8 - and shown in Figure 3.

The spatial dimensions of the array 11 are chosen
to ensure that sufficient resolution can be achieved
when interpreting the measured ground responses to
locate the leak 1.

In Figure 3 there is shown the P-wave 6, a
compressional wave, travelling from the leak 1 directly
to the accelerometer 3. The R-wave 7 is a P-wave
travelling to surface from the leak 1 and there
converted to a Rayleigh wave along the ground surface 9.
Rayleigh waves generally have a lower speed than
compressional waves. The F-wave 8 consists of a wave
along the pipe 2 - travelling at high speed along the
high density wall material of the pipe - refracting to
the surface as a P-wave to the accelerometer 3.

The signals at the various accelerometers 3 are
cross-correlated in time (by equipment not shown) with
reference to one selected reference accelerometer 10 -
the centre one in this instance. The cross-correlations
give the times of arrival of the various waves at the
accelerometer 3 in question relative to the arrival at
the reference accelerometer 10. If only the P-waves
existed, with no extra reflections, and if the ground
were homogeneous, then the relative arrival times at
different accelerometers 3 plotted against position
across the array 11 would reveal an approximate
hyperboloid shape whose extremum corresponded with the
position in the array immediately above the leak. The
hyperboloid allows not only horizontal position of the
leak 1 to be determined but also the wave speed and the

depth of the leak 1 below the ground surface 9. The
presence of other wave types and routes will corrupt the
hyperboloid, but it is still possible in principle to
determine the location of the leak 1 from the time
signals at the various accelerometers 3.

As well as the cross-correlations, an estimate of
the power in the signal from each accelerometer 3 may be
plotted against position along each array 11. The
position of the peak along each arm of the array 11
indicates the location of the leak 1. Also, the
attenuation of the signals from the accelerometers 3 as
a function of frequency will vary with position along
the array 11. This variation can be plotted against
position to give an estimate of the position of the
leak 1.

With the cross-correlation, the power variation
with position, and the variation in attenuation with
frequency with position, there will be obtained three
different indicators of the position of the leak 1.
Having three methods allows confirmation of the leak
location, and enables the method of the invention to
work even if under particular circumstances one or two
of the three methods fails.

If the leak 1 lies laterally outside the physical
dimensions of the array 11 then there is sufficient
information to determine that fact and to gain some idea
of the direction and location of the leak 1. The
array 11 can then be moved to the new location so that
an improved estimate of the leak 1 position can be made.

An example of a particularly preferred structure of
sensor apparatus, displaying details of the support for
the accelerometer, is shown in Figure 4. The

- 20 -

accelerometer 3 incorporates a conical steel tip (16) which in use is pressed into contact with the ground surface 9. The tip 16 is supported in a lower (as viewed) vibration-dampening polymer mat (12) by a number of polymer annuli (as 14) of different radii. A light stiff TUFNELL support block (15) protects the accelerometer cable. A second mat (13) provides both additional weight and environmental protection for the accelerometer cables.

Claims

1.   A method of determining the location of a leak in
an underground pipe carrying a fluid, in which method
the movement of the ground caused by the fluid as it
leaks from the pipe is listened to using sensors at a
multiplicity of positions spaced over the ground surface
and disposed within an area extending over the suspected
location of the leak, and by suitably combining and
operating upon the signal information received at each
position there is determined the actual location of the
leak.

2.   A method as claimed in Claim 1, applied to the
location of a leak in an underground water pipe.

3.   A method as claimed in either of the preceding
Claims, in which there is received and processed signal
information relating to the motion of the ground both
vertically and laterally.

4.   A method as claimed in any of the preceding Claims,
in which the multiplicity of positions at which the
motion of the ground is measured consists of a number of
discrete locations forming a two-dimensional array
disposed over the chosen area of ground.

5.   A method as claimed in Claim 4, in which the array
of positions is in the form of two orthogonally-disposed
linear arrays of equispaced positions.

6.   A method as claimed in any of the preceding Claims,
in which, where the multiplicity of positions is in the
form of an array that is linear, or has linear
components, then the line, or one of the lines, of

- 22 -

positions is aligned with the underground pipe being
checked.

7.   A method as claimed in any of the preceding Claims,
in which the detection of ground motion is effected over
an area of ground extending over the suspected location
of the leak and of lateral dimensions that do not exceed
thrice the depth of the pipe in which the leak has
occurred.

8.   A method as claimed in any of the preceding Claims,
in which the ground movement is listened to by sensors
each of which is of the accelerometer type, with a mass
of up to 100g and sensitive to frequencies up to 10
kilohertz.

9.   A method as claimed in Claim 8, in which in which
each accelerometer is provided with external damping.

10.   A method as claimed in Claim 9, in which the
damping is provided by a body of a high damping material
to hold the accelerometer in ground contact and thereby
avoid significant mounting resonance effects between the
accelerometer and the ground.

11.   A method as claimed in Claim 10, in which the body
of a high damping material is a mat that is used to hold
the accelerometer down into contact with the ground.

12.   A method as claimed in Claim 11, in which, to raise
the stiffness of the mat around the accelerometer, a
series of concentric annuli of the mat material graded
in increasing radii is assembled around the
accelerometer.

13.   A method as claimed in either of Claims 11 and 12,
in which, to add weight, a second mat is placed over the
first one.

14. A method as claimed in any of Claims 9 to 13, in
which the base of the accelerometer is conical - that
is, be shaped to have a cone whose length is suited to
the ground hardness.

15. A method as claimed in any of the preceding Claims,
in which the multiplicity of sensors in a fixed array
has its component sensors scanned sequentially in pairs,
with one sensor regarded as a reference.

15. A method as claimed in any of the preceding Claims
and substantially as described hereinbefore.

16. For use in the leak location method as claimed in
any of the preceding Claims, ground-motion detection
apparatus comprising a multiplicity of discrete ground-
motion sensors each in use contactable with the ground,
together with a body of a high damping material to hold
each sensor in ground contact and thereby avoid
significant mounting resonance effects between the
sensor and the ground.

17. Ground-motion detection apparatus as claimed in
Claim 16 and as defined in any of Claims 9 to 14.

18. Ground-motion detection apparatus as claimed in
either of Claims 16 and 17 and substantially as
described hereinbefore.

- 24 -

AMENDED CLAIMS

[received by the International Bureau on 11 March 1998 (11.03.98);
  original claims 1-18 replaced by amended claims 1-14 (2 pages)]

1.   Ground-motion detection apparatus comprising a
multiplicity of discrete ground-motion sensors each in
use contactable with the ground, together with a body of
a high damping material to hold each sensor in ground
contact and thereby avoid significant mounting resonance
effects between the sensor and the ground.

2.   Apparatus as claimed in Claim 1, wherein the
multiplicity of sensors is disposed as a two-dimensional
array.

3.   Apparatus claimed in Claim 2, in which the array is
in the form of two orthogonally-disposed linear arrays
of equispaced sensors.

4.   Apparatus as claimed in any of the preceding
Claims, wherein the sensors are each of the
accelerometer type, with a mass of up to 100g and
sensitive to frequencies up to 10 kilohertz.

5.   Apparatus as claimed in any of the preceding
Claims, wherein the body of a high damping material is a
mat.

6.   Apparatus as claimed in Claim 5, wherein, to raise
the stiffness of the mat around each accelerometer, a
series of concentric annuli of the mat material graded
in increasing radii is assembled around the
accelerometer.

7.   Apparatus as claimed in either of Claims 5 and 6,
wherein, to add weight, a second mat is placed over the
first one.

8.   Apparatus as claimed in any of Claims 4 to 7,
wherein the base of the accelerometer is conical - that

- 25 -

is, is shaped to have a cone whose length is suited to the ground hardness.

9.   A method of determining the location of a leak in an underground pipe carrying a fluid, in which method the movement of the ground caused by the fluid as it leaks from the pipe is listened to using ground-motion detection apparatus as claimed in any of the preceding Claims, and by suitably combining and operating upon the signal information received at each sensor there is determined the actual location of the leak.

10.   A method as claimed in Claim 9, applied to the location of a leak in an underground water pipe.

11.   A method as claimed in either of Claims 9 and 10, in which there is received and processed signal information relating to the motion of the ground both vertically and laterally.

12.   A method as claimed in any of Claims 9 to 11, in which, where the multiplicity of sensors is in the form of an array that is linear, or has linear components, then the line, or one of the lines, of sensors is aligned with the underground pipe being checked.

13.   A method as claimed in any of Claims 9 to 12, in which the detection of ground motion is effected over an area of ground extending over the suspected location of the leak and of lateral dimensions that do not exceed thrice the depth of the pipe in which the leak has occurred.

14.   A method as claimed in any of Claims 9 to 13, in which the multiplicity of sensors has its component sensors scanned sequentially in pairs, with one sensor regarded as a reference.
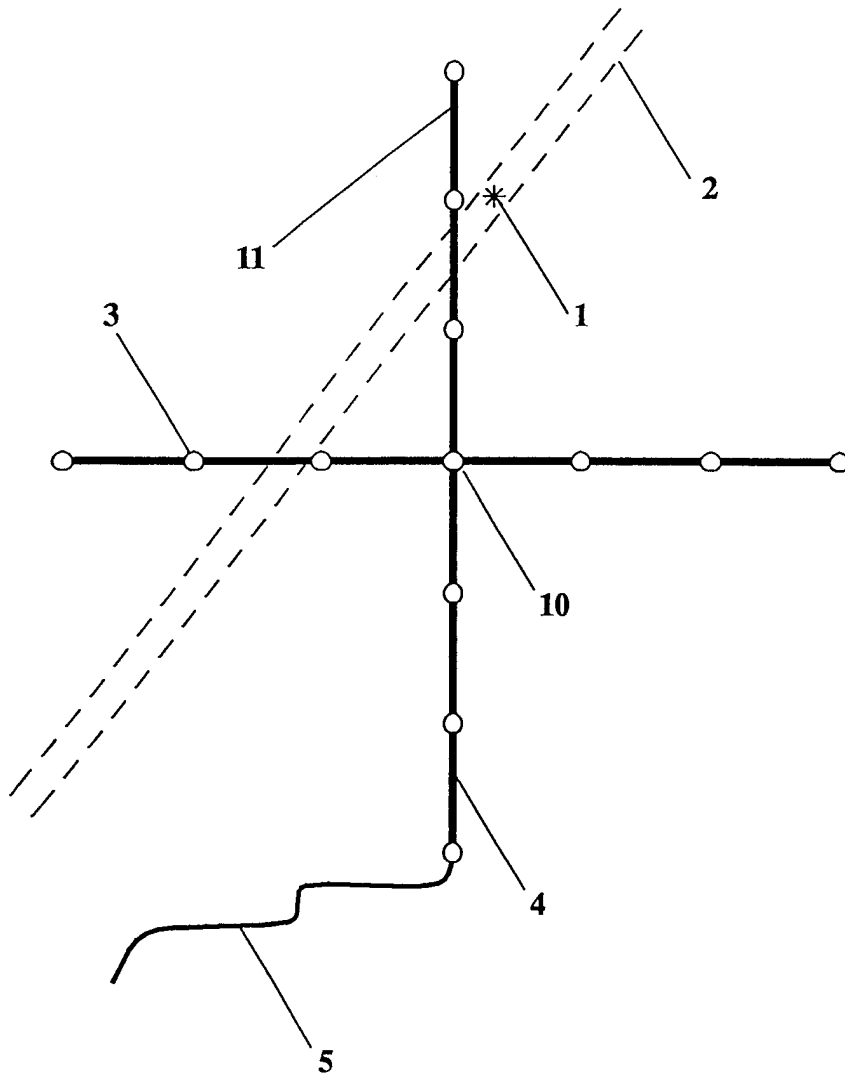
AMENDED SHEET (ARTICLE 19)
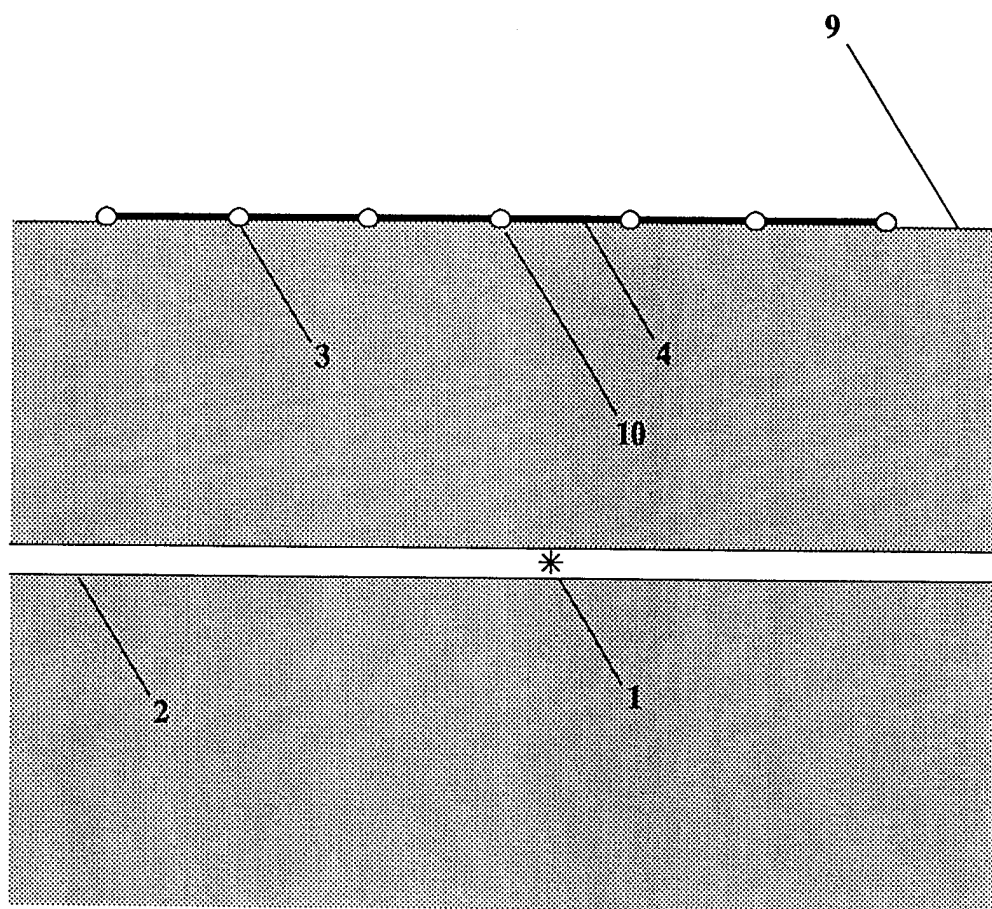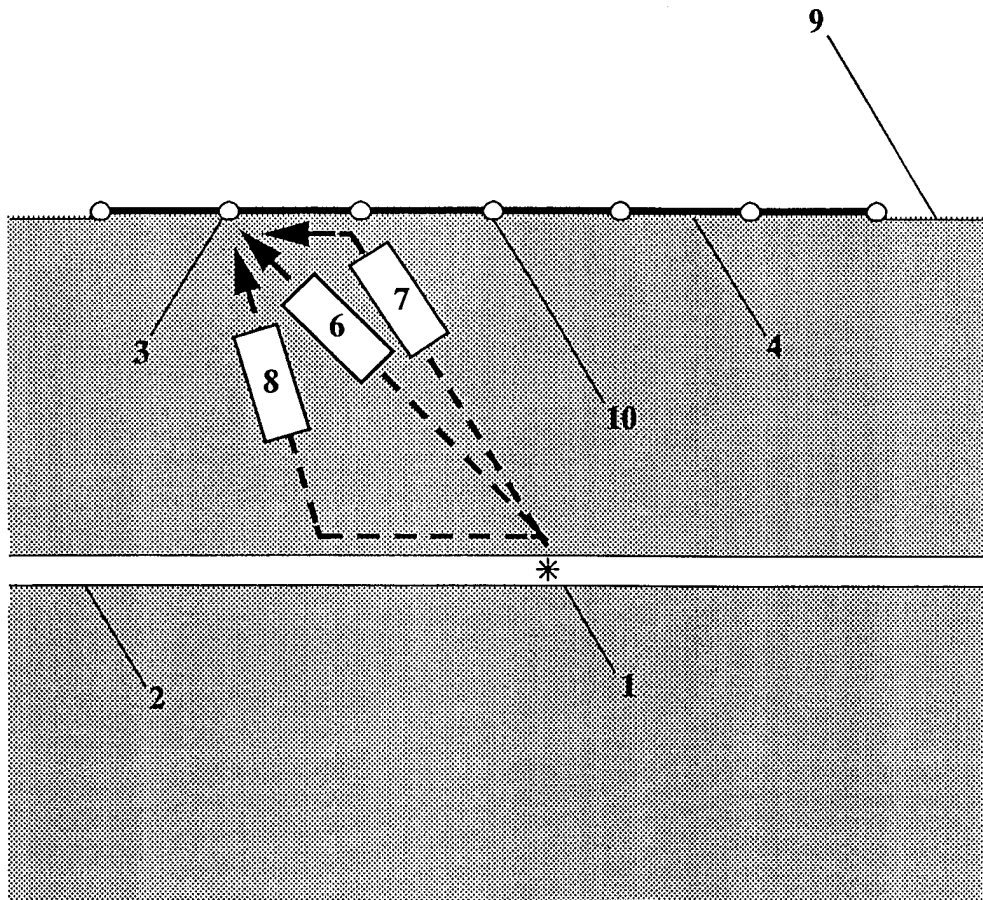
FIGURE 1

FIGURE 2

-3/4-
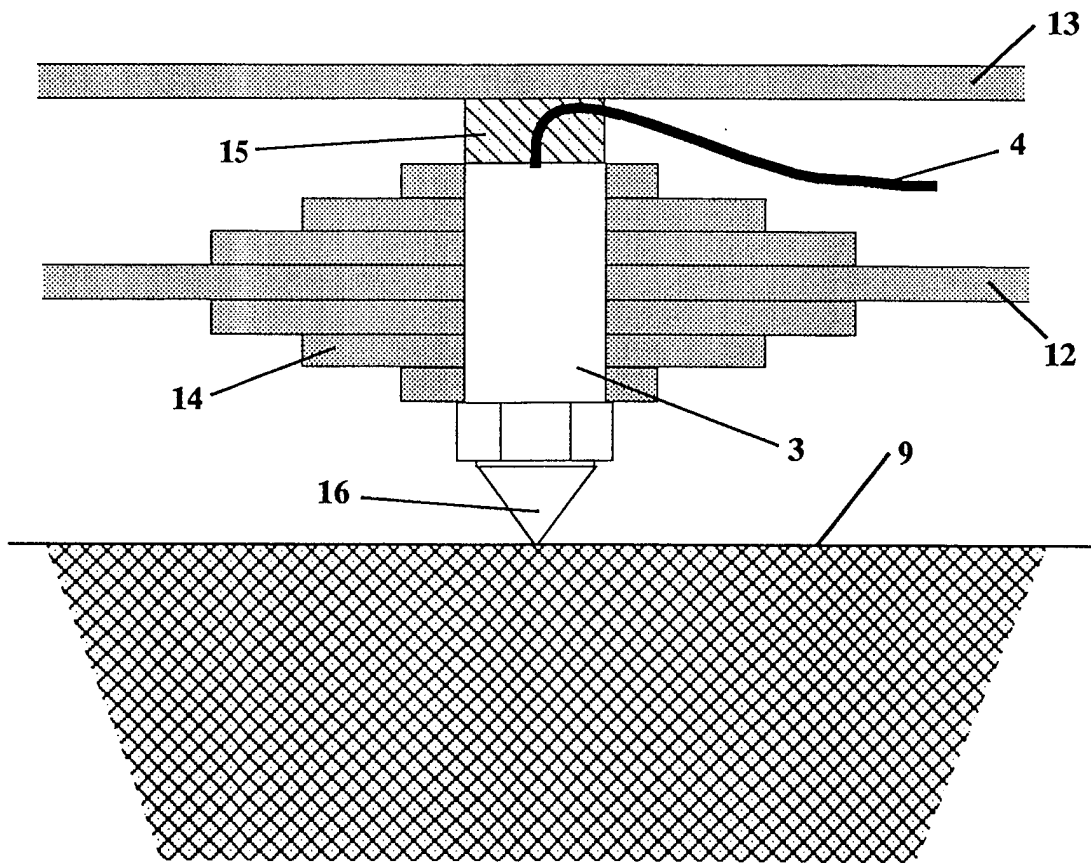
FIGURE 3

FIGURE 4

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   G01M3/24

According to International Patent Classification(IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   G01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4 697 456 A (MASER KENNETH R) 6 October 1987 see page 4, paragraph 2	1,2,4,5
Y	FR 2 503 363 A (SEBA MESS ORTUNGSTECH) 8 October 1982 see page 6, line 29 – page 7, line 20; figure 1	1,2,4,5

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publicationdate of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of theinternational search	Date of mailing of the international search report
29 January 1998	05/02/1998

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

ormation on patent family members

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 4697456 A	06-10-87	NONE	
FR 2503363 A	08-10-82	DE 3112829 A	14-10-82
		AT 386669 B	26-09-88
		CH 667737 A	31-10-88
		GB 2099995 A,B	15-12-82
		JP 1605640 C	31-05-91
		JP 2030455 B	06-07-90
		JP 58032108 A	25-02-83
		US 4457163 A	03-07-84