RETAINING WALLS ON SUBSIDENCE AREAS[1]

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Abstract: In this paper, are derived formulas for calculating the horizontal soil pressure acting on freestanding retaining walls and basement walls of structures erected on mine subsidence areas. Different work conditions resulting in different values of soil pressure in nonmined and mine subsidence areas are analyzed. An example of a structure designed using the derived formulas is also given.

Introduction

The best results in treating structures subjected to mining-induced subsidence are achieved when the problem is divided into two parts. First, the mining engineer determines the magnitude of ground movements due to mining and transfers to the designer of the structure the value of expected subsidence and its components, such as surface curvature, tilt, and strain, both tensile and compressive. Second, the structural engineer, knowing the magitudes of subsidence components, subgrade properties, such as soil capacity, specific weight, angle of internal friction, and deformation modulus, in addition to the characteristics and service requirements of the designed structure, is able to apply proper solutions to mitigate subsidence influence or to design the structure so that damage is minimized and serviceability is unobstructed by subsidence, both for existing and newly designed structures.

In this paper, the influence of subsidence on horizontal pressure acting on vertical walls is considered, taking into account different conditions of work in mine subsidence areas in relation to nonmined areas. Freestanding retaining walls (without restrains on horizontal movements) and basement walls in buildings in nonmined areas are treated identically, as loaded by active earth pressure or by pressure at rest. In areas of mining-induced subsidence, the conditions of their work are extremely different, especially in compressive zones. The horizontal pressure increases when the subsidence basin forms under the structure and can even reach the magnitude of passive pressure. The existence of increased pressure has been proven by numerous observations of basement wall deformations, when the compression zone of the subsidence trough progresses under the buildings. In older structures designed when the influence of mining on the surface was not fully recognized, the loading on vertical walls was considered to be equal to passive pressure, was assumed to be double the active pressure. Later, based on existing structures observations, it was deduced that increased pressure falls between active and passive pressures, depending on the magnitude of compressive strain.

In the U.S. literature on the subject (Speck and Bruhn 1990) an example is given (figure 1) in which a pressure greater than passive is assumed to load the basement walls. The additional earth pressure (above passive) imposed by subsidence is defined as proportionate to the deformation modulus of soil, without giving values of coefficient of proportionality. The increase in pressure is linked to secondary factors, such as steepening the slope or weakening the wall

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by subsidence below the capacity to sustain active pressure. The influence of soil strain is not considered.

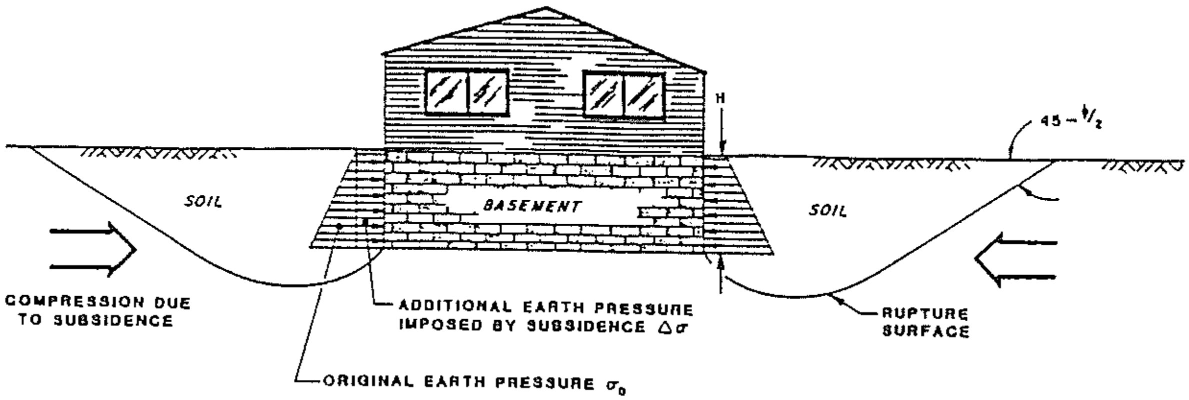

Figure 1. Earth pressure on subgrade walls of building located in compressive subsidence zone (Speck and Bruhn 1990).

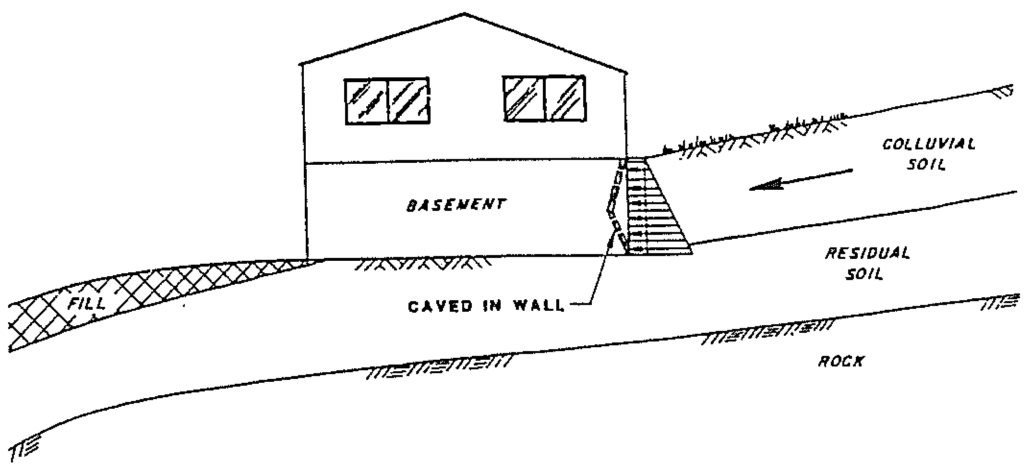

Figure 2. Earth pressure on uphill subgrade wall of building intensified by subsidence-induced hillslop instability (Speck and Bruhn 1990).

In another publication (Drumm et al. 1988) the hypothetical vertical stress distribution is considered (figure 3), derived from soil-structure interaction (i.e. dependent on relative stiffness of wall and soil). This approach also did not take into account the magnitude of compressive strain, which is of primary importance, but rather concentrate on secondary factors.

The remedial, or mitigation, means are recommended without consideration of the stresses or horizontal pressure magnitude, thus ignoring the main reason for mitigation, it means without proving the need for application of such means. Mix-up created by merging the effects of irregular or sinkhole form with regular or due trough form of subsidence implies that authors do not recognize an existence of these two forms of subsidence, which adds to the confusion in reading the cited paper. It is especially visible in the description of displacement in the tensile zone of subsidence basin.

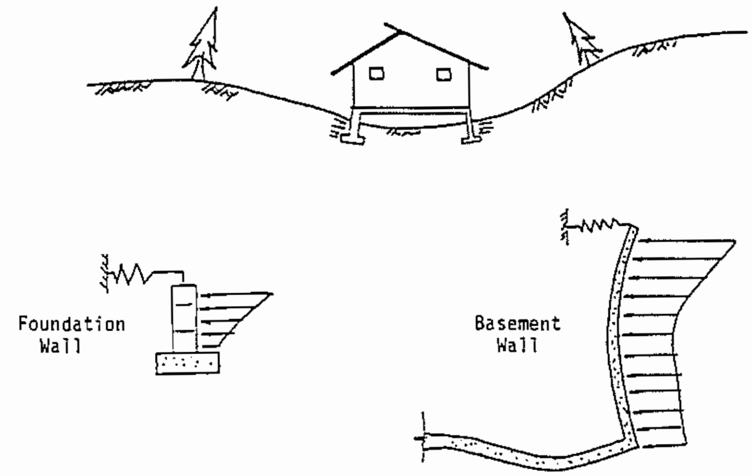

Figure 3. Schematic of plane strain idealization of compression zone (Drumm e t al. 1988).

In both of the above-mentioned papers, the increasing influence of structure dimensions on additional horizontal pressure due to compressive strain is not even mentioned.

Soil Pressure on Vertical Walls in the Compression Zone

The exact theory of soil pressure on vertical walls in mine subsidence areas has not been derived yet. It would be necessarily based on results of research in which the spread of horizontal stresses in soil halfspace had been solved. At present an approximate solution is used. The assumption is made that soil around the structure is homogeneous and isotropic, with a constant value for deformation modulus of soil in horizontal direction E_h. Figure 4 was used in the of derivation of formulas for horizontal pressure.

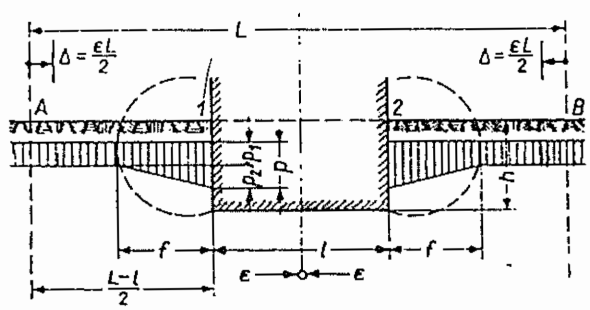

Figure 4. Disturbance zones.

The additional earth pressure (above active), due to action of horizontal strain, uniform in the entire compresive zone, and equal to p_1 is disturbed in the vicinity of the building walls by the stiffness of the structure, which restrains soil movement. Outside, in the distance "f" from the walls the influence of the building disappears and so does the disturbance of pressure. The distance "f" depends on building dimensions (length, foundation depth) and soil properties. In sections distant more than $L \geq l+2f$, where l is the length of structure, the increase of pressure due to subsidence reaches value:

$$p_1 = \epsilon E_h \tag{1}$$

in which ϵ = compressive strain due to mining.
Compressive strain in soil causes the section distant L from each other to move closer for distance Δ.

$$2\Delta = 2 \cdot 0.5 \cdot \epsilon L \tag{2}$$

In the disturbance zone, it means on length "f", pressure increases linearly, and close to the wall reaches value p. The comparision of displacements leads to:

$$0.5\ \epsilon L = \frac{p_1}{E_h}\ \frac{L-1}{2} + \frac{p_2 f}{2E_h} \tag{3}$$

Substituting equation 1 into equation 3 gives:

$$p_2 = \frac{1}{f} E_h \epsilon 1 \tag{4}$$

The additional pressure on the wall due to mining becomes:

$$p = p_1 + p_2 = \epsilon E_h (1 + \frac{1}{f}) \tag{5}$$

There are different opinions about the distance of pressure disturbence zone "f". Since additional pressure is by nature passive, it is justified to assume that the length of disturbance zone "f" is equal to the passive soil resistance wedge and:

$$f = h \tan(45^\circ + \phi/2) \approx 1.5h \tag{6}$$

so equation 5 takes the final form:

$$p = \epsilon E_h (1 + \frac{1}{1.5h}) \tag{7}$$

The deformation modulus of soil in horizontal direction E_h is generaly smaller than the vertical modulus of soil "E", which is determined by laboratory tests.

It can be taken as: $E_h = 0.4$ E, for sandy soil and $E_h = 0.5$ E, for cohesive soil.

The final soil pressure "p_o" in zones of compressive strain is equal to the sum of active pressure "p_a" and additional pressure "p":

$$p_a = \gamma h k_a - 2c \tan(45^\circ - \phi/2) \tag{8}$$

where k_a = coefficient of active pressure
$k_a = (1-\sin\phi)/(1+\sin\phi)$

$$p_o = p_a + \epsilon E_h (1 + 1/1.5h) \tag{9}$$

The passive soil pressure "p_p", is equal:

$$p_p = \gamma h k_p + 2c \tan(45° + \phi/2) \qquad (10)$$

in which γ = unit weight of soil
h = height of wall
k_p = coefficient of passive pressure
ϕ = angle of internal friction
c = cohesion of soil
$k_p = (1+\sin\phi)/(1-\sin\phi)$.

The real pressure "p_o" cannot be greater then passive soil pressure "p_p". The condition $p_o < p_p$ is always valid, so it is possible to find the zone in which p_o prevails - zone I, and zone in which p_p prevails - zone II, as shown in figure 5.

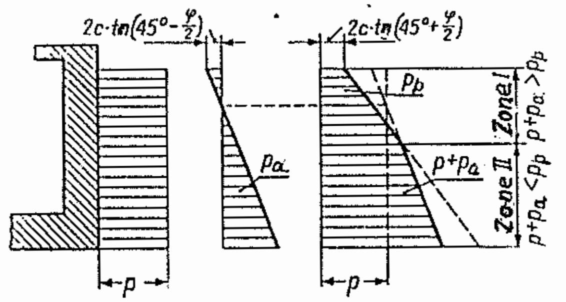

Figure 5. Pressure on wall in zone of compressive strain.

For sandy soils, it means for c=0, only first factor of sum remains, which is function of angle of internal friction ϕ.

The above-derived equations are valid for walls in which compressive strain causes movements in a direction opposite to the direction of earth pressure. However, when movements in the direction of earth pressure are possible, the actual pressure drops even as low as to the value of active pressure, just as it does in freestanding retaining walls in nonmining areas. So, this also explains why in areas of compressive strain basement walls buckle inward a few inches under additional pressure, but do not collapse. The movement due to buckling is sufficient to reduce passive pressure to the magnitude of active pressure before the walls are forced to collapse. Buckled walls are still strong enough to safely sustain active pressure.

Retaining Walls

Freestanding retaining walls designed for active pressure (figure 6), when pressure increases, tend to move in the direction of pressure by rotating or sliding, so actual acting pressure is reduced to the value of active pressure, for which the wall was originally designed anyway. The behavior described above is typical for nonmined areas. For the mine subsidence area, additional analysis should be performed.

The additional pressure $p = \epsilon E$ can be generated only when sliding or rotation in the direction of pressure is restrained. In most cases, the safety factor for rotation is larger than against sliding, so for simplicity it is assumed that

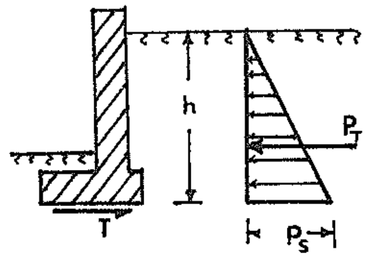

Figure 6. Retaining wall.

design the safety for sliding is critical. The maximum force the retaining wall can resist is equal to:

$$T = G\ f_m \tag{11}$$

where G = vertical load (weight) of retaining wall for unit width and
f_m = largest value of coefficient between soil and foundation.

Active pressure "p_a" and additional pressure "p" due to compressive strain produces force P_T:

$$P_T = P_A + P = 1/2\ p_a h + \epsilon E_h h \tag{12}$$

Since it is always $T \le P_T$ or $T \le P_p = 1/2\ h\ p_p$, the earth pressure cannot grow larger than the value:

$$p_s = \min[p_a + 2\epsilon E_h,\ 2Gf_m/h,\ p_p] \tag{13}$$

As a general rule, it can be concluded that loading on freestanding retaining walls in subsidence areas cannot be greater than p_s. It is obvious that the factor of safety for retaining wall against sliding using minimal values of coefficient of friction f_s, as well as for rotation, should be checked and satisfy code requirements, as for structures on non-mined areas.

The largest values of coefficient of friction f_m for applied materials should be establised by research and tests. Based on observation of existing

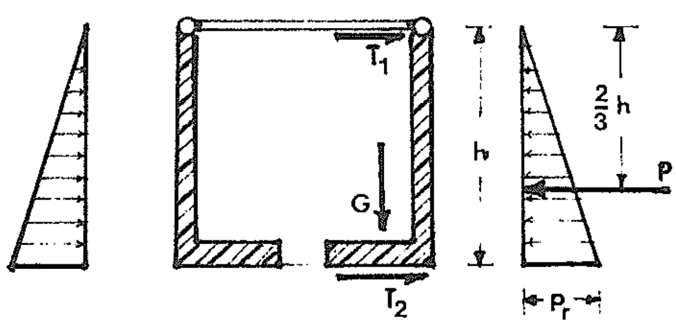

Figure 7. Schematic system of tunnel walls.

structures, mainly bridges subjected to mining subsidence, for three layers of tarpaper f_m=0.6 were used. No demage was reported to structures serving long term on mine subsidence areas when this value for f_m was used in their design.

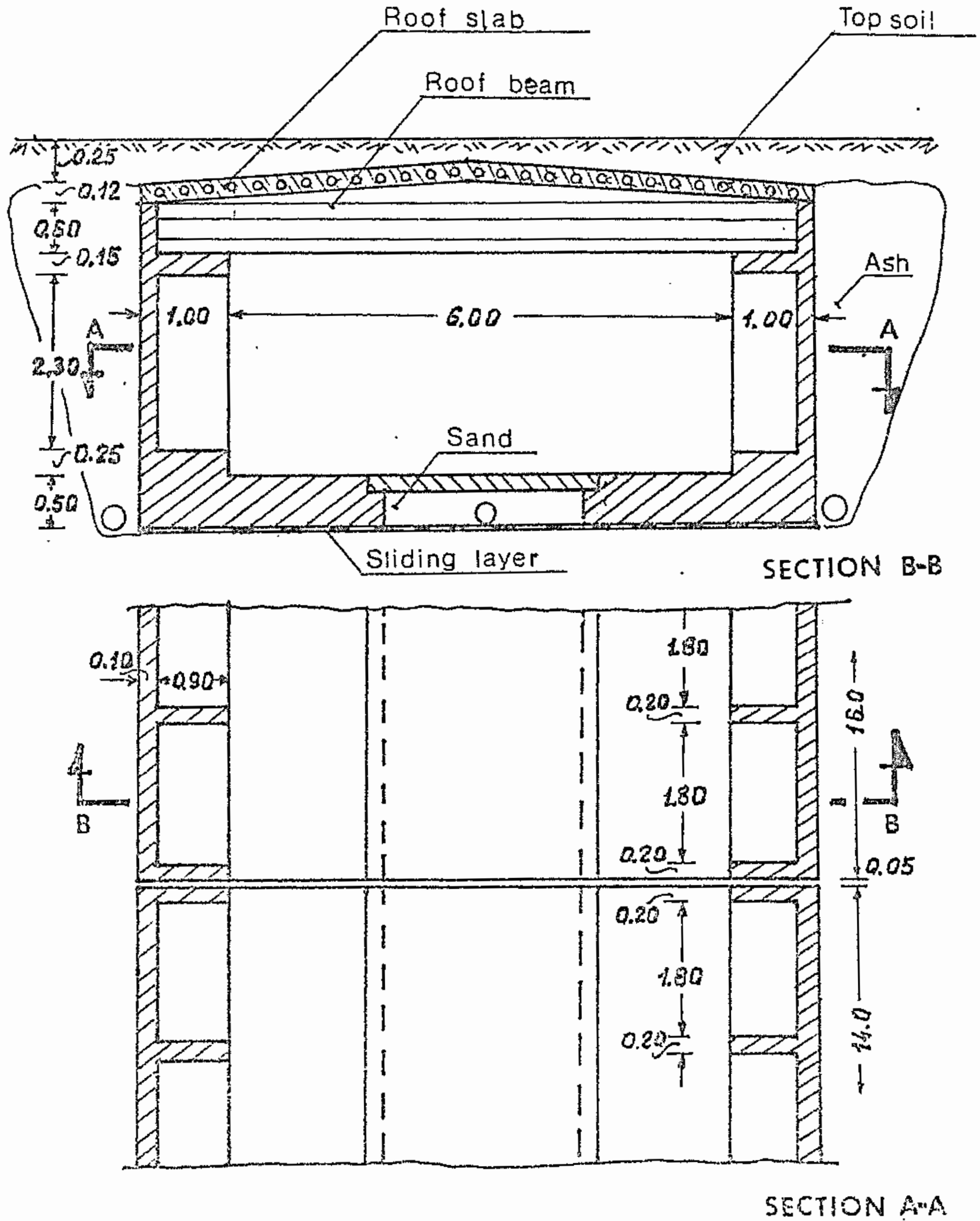

Figure 8. 6.0 m wide tunnels.

The significant reduction of loads and mitigation of mine subsidence influence can be achieved in all these cases for which the system of sliding or rotating walls under mine-induced strain is applicable. An expample of the application of the sliding walls system, the walls in tunnels for pedestrian under a traffic circle is presented here (Boczkaj et al. 1990). Figure 7 shows the method of calculating the largest possible pressure on walls.

The safety of walls was checked for active pressure with minimal coefficient of friction. Walls against horizontal movements were supported by ceiling beams on top (force T_1), on the bottom movements were restrained by friction (force T_2). The maximum resisting force T_2 was calculated using equation 11. Equilibrium condition provides the condition $T_1 = 1/2\ T_2$. Extremel horizontal pressure P is equal 1.5 T_2, which leads to the following equation for soil pressure:

$$p_r = \frac{T_2}{3h} = \frac{f_m G}{3h} \tag{14}$$

The pressure "p_r" calculated from equation 14 was almost six times smaller than pressure "p_o" according to equation 9, which would be valid for a case when sliding has not been possible. Figure 8 gives a more detailed view of tunnel sections and special construction joints placed in distances not exceeding 16 m to eliminate excessive bending moments in walls due to surface curvature caused by mining. Two seams of coal under the tunnels were removed and produced 600 mm (24 in) of subsidence. Tunnels were subjected to horizontal strain, compressive and tensile, equal 3 mm/m, or 0.003. The structure is periodically inspected and is reported in excellent shape after more then 25 years of service. It also attests to the fact that properly chosen structural systems on mine subsidence areas can be economically successful, with the total cost in the range of the cost for nonmined area.

Conclusion

The problem of loading on retaining walls and basement walls requires more research and testing, until an accurate, rigorous theory is created. However, until a such theory will is presented, the simplified, approximate methods presented in this paper can serve the purpose. Utilization of experience gained in the prevention or mitigation of mine subsidence influence can lead to substantial savings when a proper system of structure is designed.

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