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Construction of Housing in Mine Subsidence Areas

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

CONSTRUCTION OF HOUSING IN MINE SUBSIDENCE AREAS

ABSTRACT

Criteria for site exploration, risk assessment, site development and housing construction in actual and potential mine subsidence areas are recommended. Appendix A includes guidance for subsidence profile determination and a proposed mathematical model which may aid in predicting complex subsidence patterns. Appendix B includes a commentary and proposed equations and procedures for the design of rigid and flexible foundations.

Keywords: Design criteria; foundation design; geotechnical engineering; housing construction; mine subsidence; mining; settlement; structural design; structural engineering.

NOTATION

Special notation for subsidence parameters, s, e, v and g:

1. A small letter designates magnitude at any point.
2. A capital letter designates the largest magnitude occurring in a given subsidence profile.
3. A capital letter with subscript "max" designates the largest magnitude in a fully developed subsidence profile, which is in most cases the largest possible magnitude.

a	= subsidence factor = S_{max}/m
d	= depth below grade
dA	= incremental area of mined seam
D	= design dead load
E	= Young's Modulus (used only to denote "stiffness parameter" EI)
$\pm e$, $\pm E$, $\pm E_{max}$	= horizontal ground strain, + = tensile, − = compressive
f	= friction coefficient
g, G, G_{max}	= slope of subsidence profile
h	= depth of mined seam below surface
I	= moment of inertia
ℓ	= horizontal length of structure
L	= design live load
m	= thickness of mined seam
M	= moment
p(r)	= influence function
P	= a surface point
r	= horizontal projection of radial distance
R	= radius of curvature of a subsidence profile in any point
R_{min}	= minimum radius of curvature in a given subsidence profile
s, S, S_{max}	= subsidence settlement
v, V, V_{max}	= horizontal displacement
$\overline{V}$	= shear
w	= width of mined panel
$\overline{w}$	= unit gravity load on foundation element
x	= horizontal distance coordinate
y	= vertical distance coordinate

α = secant angle of deflected foundation

Δ = "equivalent" cantilever deflection of deflected foundation

Δ_s/ℓ = measure of differential settlement

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1. INTRODUCTION

1.1 PREAMBLE

This report was prepared by the National Bureau of Standards (NBS) in behalf of the Department of Housing and Urban Development (HUD). The purpose of the report is to suggest measures to mitigate damage to housing in areas where subsidence might occur as a result of past or future underground mining. Strip mining problems are not considered in this report.

Many areas in the United States are underlain by abandoned mines, and many more areas will be undermined in the future. As mine cavities collapse they cause settlement and ground distortions on the surface which may damage or destroy buildings and utilities. If HUD is to finance construction of housing in such undermined areas, there is a need for the prior assessment of subsidence risks and for preventive measures to minimize effects of subsidence settlements. A particularly difficult risk evaluation problem exists in areas underlain by abandoned coal mines which have been mined by the commonly used room and pillar method, where underground cavities are supported by coal pillars which are subject to slow deterioration and eventual collapse.

While the measures suggested herein can aid HUD officials, developers and consulting engineers in assessing and attenuating subsidence risks, they cannot be a substitute for the professional judgment of a qualified consulting engineer, who must use his knowledge of the state of the art in engineering and geology as well as his knowledge of specific site conditions to arrive at a recommendation.

The recommendations in this report were prepared in 1977 and reviewed by a panel of consultants experienced in mine subsidence problems. The recommendations should be updated from time to time as the state of the art advances and U.S. field data become available.

1.2 STRUCTURE OF REPORT

The report addresses three problems: site exploration and evaluation; site development, and housing construction. Site exploration and evaluation, as well as criteria that could be used by HUD to determine the suitability of sites for the construction of housing, are presented in section 2. Section 3 discusses criteria for site development, housing construction, and utility lines based on the results of a site evaluation. Section 4 deals specifically with structural design features to mitigate subsidence damage. Appendix A provides information on the determination of subsidence effects. Appendix B contains a commentary and derivations of proposed equations and procedures for the design of rigid and flexible foundations.

2. SITE EVALUATION AND ACCEPTANCE

2.1 GENERAL

A site evaluation should be conducted under the direction of a registered professional engineer with recognized qualifications in geotechnical engineering, and with past experience in mine subsidence investigations. The following sites should be evaluated to determine mine subsidence risks:

1. Sites underlain by, or adjacent to, abandoned or active mines;

2. Sites located in, or adjacent to, areas where mineral rights were acquired by mining companies;

3. Sites which are underlain by, or adjacent to, mine waste deposits.

The scope of the required investigation will depend on site characteristics, planned development and available information and should be determined by the engineer and HUD on a case-by-case basis.

HUD may request that the technical staff conducting the evaluation include one or more of the following professionals:

1. A geotechnical engineer

2. An engineering geologist

3. A mining engineer

4. A groundwater hydrologist

5. A structural engineer

A site evaluation report should be submitted to HUD for consideration. HUD may disapprove the recommendations, require added documentation, or impose additional restrictions on construction or site development in order to minimize risks to the life, health and property of those who reside, work or visit at the site.

2.2 OBJECTIVE

The objective of the site evaluation is to provide the information and documentation needed to determine whether construction of housing is feasible on the site and whether, and under what conditions, HUD would finance the construction of housing under one of its programs.

2.3 SCOPE

The report on the site evaluation should contain the information required for the assessment of subsidence risks as outlined in section 2.4, and, as a minimum, the following:

1. Assessment of the site in accordance with section 2.6.

2. Special provisions for site development in accordance with section 3.

3. Structural design requirements in accordance with section 4.

2.4 CRITERIA FOR SITE ASSESSMENT

2.4.1 Rating of Sites

On the basis of the subsidence risk evaluation, sites should be placed in one of three categories:

1. Unsuitable

2. Conditionally suitable

3. Unconditionally suitable

On "unsuitable" sites HUD should not finance construction of housing.

On "conditionally suitable" sites HUD should finance construction subject to the criteria in sections 3 and 4 of this report.

On "unconditionally suitable" sites HUD should permit construction of housing and the criteria in sections 3 and 4 of this report should not apply.

2.4.2 Unsuitable Sites

The following sites should be considered unsuitable for the construction of housing:

1. Sites which are deemed to be subject to a significant subsidence risk (see section 2.5) and are located directly over a geological fault or some other discontinuity in the rock strata which could lead to abrupt changes in the subsidence profile.

2. Sites in the vicinity of mines or mine waste deposits which are experiencing, or carry a significant risk of, spontaneous combustion.

3. Sites where there is a significant risk of accumulation of dangerous gases.

4. Sites located over, or in the immediate vicinity of, mined seams, and where it is deemed infeasible to obtain the necessary data for subsidence risk evaluation.

5. Sites where anticipated subsidence effects are so severe that even buildings with foundations that are independent of support conditions could be endangered by excessive tilting or other failure modes.

6. Sites where there is a significant risk of downwash (i.e., migration of soils into voids or fractures).

2.4.3 Conditionally Suitable Sites

The following sites should be considered conditionally suitable for the construction of housing:

1. All sites which are deemed to be subject to a significant subsidence risk and which are not classified as unsuitable.

2. All sites directly served by utilities and/or access roads which are subject to a significant subsidence risk.

2.4.4 Unconditionally Suitable Sites

All sites in which all building foundation elements are located outside the zones deemed to be subject to a significant subsidence risk, and which are not directly served by utilities or access roads located in areas deemed to be subject to a significant subsidence risk.

2.5 <u>SUBSIDENCE RISK EVALUATION</u>

2.5.1 General

Ideally, a risk assessment should be based on the probability of occurrence of subsidence of given magnitudes. However, the determination of these probabilities is not within the reach of present knowledge and experience. Thus, the following approach is recommended:

1. Make an assessment of whether significant subsidence is likely to occur during the service life of the housing units. The "service life" is assumed to be 50 years for buildings of three stories or less and 100 years for other buildings.

2. If it is decided that no significant subsidence is likely to occur during the service life of the buildings, no specific precautions are necessary.

3. If the safety margin against significant subsidence is not judged adequate, recommendations should be based on the most severe condition that can reasonably be anticipated.

Several possible strategies are available to reduce subsidence risk:

Active Mines

1) Purchase pillar support in the mine.

2) Delay construction until subsidence is complete; found structure on shallow footings.

3) Design for subsidence; found structure on shallow footings.

   a. A specially designed raft foundation could protect the buildings from damaging horizontal strains and distortions.

   b. The buildings could be made stiff enough to resist anticipated horizontal strains and distortions.

   c. The buildings could be made flexible enough to accommodate anticipated horizontal strains and distortions without suffering unacceptable damage.

   d. Forces acting on the foundation could be reduced by low-friction layers or bearings, protective layers of compressible soil, or other means.

   e. Buildings and utilities could be designed to allow for corrective measures, such as jacking, which could compensate for anticipated effects of subsidence.

Abandoned Mines

1) Backfill the mine or construct grout columns at mine level, found structure on shallow footings.

2) Found structure on drilled piers extending below mine floor level.

3) Found structure on shallow footings and design for subsidence.

   a. A specially designed raft foundation could protect the buildings from damaging horizontal strains and distortions.

   b. The buildings could be made stiff enough to resist anticipated horizontal strains and distortions.

   c. The buildings could be made flexible enough to accommodate anticipated horizontal strains and distortions without suffering unacceptable damage.

   d. Forces acting on the foundation could be reduced by low-friction layers or bearings, protective layers of compressible soil, or other means.

   e. Buildings and utilities could be designed to allow for corrective measures, such as jacking, which could compensate for anticipated effects of subsidence.

4) Collapse the mine and found structure on shallow footings (not ordinarily recommended).

5) Remove all material to the floor of the mine and replace with an engineered fill. Found structure on shallow footings.

6) Relocate structure to area where adequate pillar support is available or where there are no mining problems.

All these approaches could be considered if it can be demonstrated that the criteria stated in section 2.5.4 are satisfied.

2.5.2 Objective of Subsidence Risk Evaluation

The objective of the subsidence risk evaluation is to assess the risk of subsidence damage to housing units or their utilities and access roads and to recommend measures which will reduce these risks to levels acceptable to HUD.

2.5.3 Criteria

1. The recommended site assessment (section 2.4) should be based on the most severe subsidence conditions that can reasonably be anticipated.

2. If it is concluded that there is a significant subsidence risk, site improvements, utilities, roads and buildings should be designed in accordance with sections 3 and 4, for the most critical anticipated subsidence profile characteristics.

3. If compensation for anticipated subsidence effects by corrective measures is recommended, the recommendation should include proposed arrangements to insure the prompt implementation of such measures.

2.5.4 Assessment of Significant Subsidence Risk

2.5.4.1 Definition of "Significant Subsidence"

"Significant subsidence" is any subsidence which could cause damage or disruption unacceptable to HUD. Subsidence is deemed significant if any of the following conditions occur:

1. The horizontal ground strain at any location exceeds 0.05 percent.

2. The maximum length change in the foundation soil attributable to horizontal strain at any building exceeds 3/4 in. (2 cm) over the length of the building foundation in any direction.

3. The minimum slope of sewers or storm drains is diminished below the minimum allowable slope, or the maximum slope increased above the maximum allowable slope in accordance with FHA Minimum Property Standards.

4. The overall total subsidence of the site impedes drainage or increases the risk of flooding above that acceptable to HUD.

2.5.4.2 Determination of the Subsidence Profile

The determination of whether subsidence caused by a given subsurface condition will be significant should be made on the basis of the most critical subsidence profile characteristics associated with the subsurface condition.

The most critical subsidence profile with respect to a particular location is not necessarily associated with the maximum possible vertical displacement at that location. The critical parameters associated with building damage are maximum possible horizontal strain, maximum possible slope and maximum possible curvature. On the other hand, with respect to utilities and risk of flooding on the site, the maximum settlement may be critical. Thus, if a large area is underlain by a mined seam that could collapse, full, as well as partial collapse must be considered in order to determine the most critical conditions for any particular location on the site.

The engineer should determine the subsidence characteristics in accordance with the subsurface and topographical conditions on the site. While each site requires special consideration, general guidance on the determination of the subsidence profile can be derived from information in appendix A.

2.5.4.3 Ongoing or Anticipated Mining Operations

If there are ongoing mining operations which could cause subsidence on the site or if mineral rights for seams under the site are owned by mining companies, HUD should consider two options:

Option 1: If the mining operation is within a jurisdiction which does not require protection of buildings and utilities on the site, such as through providing coal pillar support and if the mining companies make no special provisions for such protection, construction might be delayed until subsidence associated with mining is complete, or if construction is not delayed, the criteria in section 2.5.3 should be satisfied, assuming that part or all of the mined seam(s) could collapse during the service life of the buildings.

Option 2: If measures acceptable to HUD are planned in compliance with protective legislation or binding agreements between the mining companies and the developer, the criteria in section 2.5.3 could be waived under the following conditions:

1. Building sites are adequately protected by restricting mining operations under the sites in order to prevent occurrence of significant subsidence where building foundations are located.

2. Provisions acceptable to HUD are made for the restoration of utilities, access roads and landscaping after disruption by subsidence occurs.

3. It is documented to the satisfaction of HUD that there is no evidence of unacceptable risk of downwash, or unacceptable risks to occupants such as rupture of gas lines.

In lieu of the measures in (1) and (2) HUD may consider other protective measures such as harmonic extraction[1/] or waste stowing for subsidence control if it is adequately documented that the risk of significant subsidence is not unacceptably high.

2.5.4.4 Abandoned and Inactive Mines

2.5.4.4.1 General. Several factors enter into a judgment as to whether subsidence is more predictable in the case of abandoned mines as compared with active or planned mining. Overall, subsidence over abandoned mining is probably more difficult to predict. First, the probability of finding mine maps decreases with time, and an accurate mine map is an essential tool for predicting subsidence. Further, many abandoned mines are shallow and the mine workings tend to be irregular in older mines. Subsidence over shallow mining is hard to predict because near-surface geologic processes tend to add complicating factors. Also the greater regularity of extraction and pillar arrangement characteristics of modern mining presents a more uniform subsidence potential than irregular patterns of much early mining which left unsupported roof spans of varying width. Finally, longwall extraction is increasing in the U.S. (though still far less common than room and pillar mining), and subsidence prediction over complete extraction panels is easier than over room and pillar workings.

The recommendations in this section could be considered for abandoned or active or planned mines if accurate and reliable data can be supplied on the location, size and characteristics of mined panels and support systems.

2.5.4.4.2 Engineering Analysis. An engineering analysis should be conducted which considers, but is not necessarily limited to, the following limit states:

[1/] Harmonic extraction is a method of mining in which the sequence and configuration of material extraction is designed to minimize surficial horizontal strains.

1. Full or partial collapse of mine cavities by structural failure of support systems and roofs;

2. Consolidation settlements by creep of roofs and pillars or by volume change in compressible layers;

3. Migration of soil into voids or fractures;

4. Spontaneous combustion and accumulation of dangerous gases.

The engineering analysis should be conducted in accordance with the professional judgment of the engineer and should be directed toward choosing between one of the following options relative to constructing above the mined out area:

1. Permit Subsidence of the Ground Surface

   a. Found structure on shallow footings and design for subsidence of structure.

   b. Found structure on drilled piers extending below mine level, prohibiting subsidence of structure but not surrounding areas.

2. Prohibit Subsidence of the Ground Surface and Found the Structure on Shallow Footings.

   a. Construct grout columns at mine level.

   b. Backfill the mine with fly ash, coal waste, or other suitable material.

   c. Remove all material to the floor of the mine and replace with an engineered fill.

Specific factors to be considered in estimating the subsidence profile that might develop at a particular site relative to option 1a are presented in the following paragraphs. Quantification of these factors even with an extensive program of investigation is difficult, making definition of subsidence profiles above abandoned mines generally very uncertain. Options 1b, 2a, 2b and 2c are often more appealing than Option 1a, but they are also more expensive, and Option 1a should therefore not be discounted without a fair evaluation. In addition, one should also consider the possibility of relocating the structure to an area where there is clearly ample pillar support or mining is not a problem.

The limit states that should be considered in an engineering analysis in conjunction with possible subsidence effects are further discussed hereafter:

(1) Full or partial collapse of mine cavities by structural failure of support systems and roofs:

Structural failures could include single pillar failures, progressive multiple pillar failures (squeeze), roof failures and punching shear failures.

Assumed loading conditions should include loads exerted by the overburden, load effects associated with ground water, including possible effects of groundwater fluctuations, and loads imposed by buildings and proposed re-grading.

The strength of the support systems should be evaluated with due consideration of anticipated deterioration during the service life of the building(s), including oxidation of rock exposed to air, spalling, erosion, and other effects.

In view of the uncertainties inherent in any engineering analysis involving rock and soil deposits, and of the strength variability of rock and soil, adequate safety margins should be assumed. The safety margins against yielding and collapse should be stated in the report.

(2) Settlements by creep and volume change of compressible layers:

Settlements in addition to those normally expected as a result of soil and loading conditions could be caused by the following:

Creep deformation of heavily loaded support pillars and roofs; punching of pillars into compressible clay layers, interbedded with rock; and deterioration, settlement and erosion of unconsoidated deposits of mine wastes. The exploration should be adequate to permit a reasonable estimate of the magnitude and rate of such settlements. Effects of creep deformation are generally very difficult to predict.

(3) Migration of soils into voids or fractures:

Migration of soils is most frequently caused by the erosion of overburden associated with the percolation of water into drained cavities. The consequences of downwash can be catastrophic when large bodies of water, such as rivers, lakes or ponds are located above drained mine cavities, or when the drainage pattern on the site tends to accumulate runoff.

Downwash tends to develop along fault zones, drill holes which were not grouted, or other discontinuities in the rock layers, if these are overlain by permeable soils. Catastrophic blowouts can occur when drained mine cavities are isolated from adjacent large bodies of surface water by impervious seals or by relatively thin layers of clay. Flooding condition with a 100 year recurrence interval should be considered when the risk of such a blowout is evaluated.

In addition to adequate exploration of surface conditions and groundwater hydrology, topographic features should be carefully examined for telltale signs of drainage into mine cavities.

HUD should not finance construction of houses if there is a significant risk of downwash, since the magnitude and characteristics of resulting settlements cannot be predicted.

(4) Spontaneous Combustion

The history of, and potential for, spontaneous combustion in mine cavities as well as in deposits of mine wastes must be investigated. HUD should not finance construction over sites which have evidence of, or a substantial risk of, spontaneous combustion.

2.6 SITE EXPLORATION

2.6.1 General

The information outlined in this section is directly related to the assessment of subsidence risks. Additional information may be needed for other design and construction requirements. "Pertinent information" is herein defined as the information determined to be necessary by the engineer for assessing subsidence risks. HUD may request additional information if the data provided are considered inadequate or unreliable.

2.6.2 Scope

Data obtained in the site exploration should, in general, include the following:

1. Records of mining activity as outlined in 2.6.3.

2. Summary of evidence of subsidence damage as outlined in 2.6.4.

3. Pertinent information on mined seams under, and adjacent to, the site as outlined in 2.6.5.

4. Topographic data as outlined in 2.6.6.

5. Pertinent information on the geological structure of the area and the physical properties of the rock strata as outlined in 2.6.7.

6. Pertinent information on the overburden as outlined in 2.6.8.

7. Pertinent information on the groundwater hydrology as outlined in 2.6.9.

2.6.3 Mining Activity and History

The purpose of the study of mining activities and history is:

1. To determine whether planned or ongoing activity could cause subsidence at some future time, during, or after completion of construction on the site.

2. To get a better appraisal of the condition of the mined veins and of the storage of mine wastes, and locations of permanent support beneath buildings.

3. To ascertain past collapses and local failures which could give an indication of similar events in the future.

4. To appraise the length of time during which support systems have been exposed to air, in order to better appraise their strength and durability.

5. To ascertain past and present fluctuations in the groundwater table or other events associated with dewatering, such as blowout of impervious seals.

6. To help ascertain the presence of dangerous gases.

7. To get information on the regularity of the mining operation in the past, in order to assess whether present or planned future activities can be expected to occur at their scheduled timing.

8. To determine ownership of mineral rights which may affect future operations.

9. To determine whether in the past, mining companies owned the land as well as the mineral rights and thereby had an incentive to minimize subsidence effects.

The study should cover available data from mining companies, municipalities, state agencies, and the Bureau of Mines. All the pertinent information should be included in the report.

2.6.4 Summary of Evidence of Subsidence and Subsidence Damage

The purpose of this information is to determine whether subsidence occurred in the area and to observe the characteristics of the subsidence. This information is important for the subsidence risk evaluation.

The study would normally include:

1. Study of topographic maps and aerial photographs, including, if possible, comparison of maps and photographs taken at various times.

2. Evidence on pending or past damage claims (information in the files of state agencies, building officials, newspaper reports, and information from mining and utility companies). As an example, information on damage claims in the Commonwealth of Pennsylvania since 1961 can be obtained from the Mine Subsidence Insurance Firms, Pennsylvania Department of Environmental Resources.

3. Field reconnaissance of structural damage to existing buildings and of any evidence of subsidence.

Whenever possible the magnitude of the past subsidence should be determined.

2.6.5 Mined Seams

The purpose of the study of mined seams is to provide pertinent information on the location, size, and stability of mined workings including shafts and access tunnels to assist in evaluating:

1. The risk of collapse or significant deformation of supports, pillars, roofs and floors.

2. The location and extent of possible areas where deformations or collapse could occur.

3. The expected maximum vertical displacement caused by such deformation or collapse.

4. The risk of significant gradual or sudden ground or surface water infiltration into drained cavities and possible paths of such infiltration if they can be identified.

5. The risk of gradual deterioration of support systems, floors and roofs.

6. The risk of collapse triggered by the mining of adjacent seams.

7. The presence of, or potential for, spontaneous combustion and formation of dangerous gases.

The area and depth to be covered by the study, as well as the extent of the required information should be determined by the engineer. HUD may require additional data before issuing mortgage insurance or direct funding.

In most cases whatever data are available can be obtained from State and Federal offices of the Bureau of Mines, state mining and geological agencies, mining companies, and building officials. The Bureau of Mines maintains Mine Map Repositories in Denver, Colorado (for areas west of the Mississippi); in Pittsburgh, Pa. (for areas east of the Mississippi); and in Wilkes-Barre, Pa. for the anthracite coal region of northeastern Pennsylvania. The Engineer should evaluate the reliability of this information and supplement it if necessary by field inspection, borings, borehole photography and other forms of geotechnical exploration and laboratory or in-situ tests of rock or soils.

Desired information might include, but not necessarily be limited to, some or all of the following items:

1. Location, depth, dip, strike, and mined thickness of seams.

2. Amount, characteristics, and methods of placement of mine wastes deposited in the voids after mining, if any.

3. Method by which the seams were mined (i.e., room and pillar, longwall, extraction ratio, date of mining, etc.).

4. Configuration of the mine, including size and location of supports. This includes vertical alignment of supports when successive seams were mined at different elevations. The location of the mine relative to the benchmarks at ground surface must be determined with certainty.

5. Information of rock characteristics in addition to the general information outlined in section 2.6.7 including the following:

   For supporting pillars:

   Strength characteristics of the pillar material;

   Weathering characteristics of the pillar material due to exposure to air and other potential effects;

Presence of clay seams, or other possible weak or weathering layers and their characteristics;

Planes of weakness and their inclination.

For the roofs over mined seam:

Strength characteristics of rock, including tensile strength;

Weathering characteristics;

Presence of weak seams;

Planes of weakness and their inclination.

For the floor underlying mined veins:

Strength characteristics of rock strata or underlying clay.

The information in item 5 may not be necessary under the following conditions:

a. The seam is collapsed or was successfully backfilled.

b. A sufficient amount of pillar support was left in the mine uniformly distributed over the area of the mined panel and the minimum dimension of supporting pillars left in place is 20 ft by 30 ft (6m x 9m).

6. General information on the condition of mined seams.

7. Information on seams that collapsed or were backfilled.

8. Presence of, or potential for, spontaneous combustion and formation of dangerous gases.

9. Presence of possible paths for infiltration of significant quantities of ground or surface water into mined cavities, as well as risk of sudden rupture of impervious seals which prevent water infiltration.

2.6.6 Topographic Data

Adequate topographic information is necessary for a determination of subsidence profiles and should be included, using suitable horizontal scales and contour intervals. Topographic maps should also be examined for characteristic features associated with past subsidence, such as depressions. If no water accumulates in such depressions this may be an indication that surface water drains into mine cavities. If the site was graded, topographic surveys taken prior to grading should be examined for such evidence. The topographic study, in some instances, should include the study of aerial photographs taken from low elevations and other special techniques. The topographic data should include accurate information on the location of mine-waste piles and disposal areas. Topography (angle of slope) also has an effect on the aerial extent of the reserve coal pillars that must be left in place to prevent subsidence.

2.6.7 Geology and Physical Properties of the Rock Formations

The purpose of the geological study is to provide pertinent information on the lithology and stratigraphy of the site to assist in evaluating whether:

1. Roofs of mined seams might cave or bend even though supporting pillars are judged strong enough.

2. There is evidence of unmined seams which could be mined in the future.

3. There is evidence of zones of weakness, such as clay seams which could increase subsidence risk and affect subsidence patterns.

4. There is evidence of faults which could alter the nature of subsidence and increase risk.

5. There is evidence of fracture zones and faults which could facilitate the percolation of larger quantities of water into mined seams and thereby cause downwash of overburden.

6. There is significant seismic risk which should be taken into consideration.

The area and depth covered by the study and the scope of the data acquired should be determined by the engineer. General information is usually available. If extensive field investigation is required, the cost of the study may in some instances exceed the benefit derived from site development.

Overall information on the geology of many areas is available in the geologic literature; guidance to pertinent geologic maps and reports may be obtained from the U.S. Geological Survey and the appropriate State geological agencies. More specific information on individual undermined areas may be available in files of the U.S. Bureau of Mines, mining companies, building officials, and various State and local agencies. It is probable that in most instances this information will have to be verified and supplemented by field exploration, but laboratory testing of rock samples will probably be warranted only in rare instances.

In addition to pertinent information on the rock strata and their position, unmined seams, and on the physical properties of the rock formations, a special effort should be made to identify any evidence of faults and other geological disturbances, as well as weak and fractured rock zones which could cause abrupt discontinuities in the subsidence profile.

2.6.8 Overburden

The purpose of the soil exploration is to provide sufficient information on the depth and characteristics of overburden for a determination of:

1. The possibility of discontinuities in the subsidence profile and crack formation due to the proximity of bedrock to the surface or other factors.

2. The risk of loss of support beneath foundations due to migration of soil into cavities and fractures.

3. The appropriateness of specific foundation designs proposed for the site.

4. The presence of potentially unstable, corrosive, combustible, or burning mine wastes, or of dangerous gases.

The extent of the area covered, the number, location, and depth of boreholes, and the amount of field and laboratory testing should be determined by the engineer.

Data can sometimes be obtained from borings and soil tests made for previous projects. However, generally, a field exploration will have to be conducted. The exploration should provide information necessary to determine the overall conditions at the site, as well as any specific problems associated with a particular building. The following data are specifically related to the subsidence problems:

1. Thickness and profile of soil and weathered rock.

2. Permeability and potential for soil migration through fractures.

3. Presence and stability of mine wastes stored at the ground surface. If mine wastes are present:

presence of combustion;

presence of dangerous gases;

potential for spontaneous combustion and formation of dangerous gases;

weathering effects;

unusual material characteristics such as high compressibility and risk of collapse or liquefaction.

Care should be taken to grout or otherwise seal drill holes after their completion if they could provide a path for surface water percolation into drained mine cavities.

2.6.9 Groundwater Hydrology

The purpose of the study of the groundwater hydrology is to provide enough information on the ground and surface water for a determination of:

1. Whether mined seams, shafts and underground tunnels are permanently submerged, permanently exposed to air, or alternately submerged and exposed.

2. How the groundwater elevation is controlled and how it is expected to fluctuate.

3. Whether a sudden change in groundwater elevation could occur because of the proximity of large bodies of surface water.

4. Whether potholes could develop by percolation of water into drained mine cavities, or by the rupture of impervious seals.

Information on the groundwater hydrology can be obtained from U.S. agencies, State agencies, building officials and mining companies. Information on availability of published or open-file maps and reports on groundwater hydrology can be obtained from the U.S. Geological Survey and from State water-resource agencies. The U.S. Corps of Engineers and the Water and Power Resources Service (formerly the Bureau of Reclamation) have groundwater data at sites of their construction projects. Local hydrologic information may be available from county and municipal agencies. In addition, the Bureau of Mines has groundwater information for the anthracite coal region. This information may have to be supplemented by observation wells and studies of surface waters, their characteristics, and seasonal fluctuations. The following data are related to the subsidence problem:

1. The groundwater level and its present, and potential future fluctuations.

2. Sources of groundwater recharge.

3. Man-made controls which could be abandoned or malfunction.

4. Bodies of surface water which could potentially cause sudden water penetration into drained mine cavities.

3. SITE DEVELOPMENT

3.1 GENERAL

HUD should not finance housing construction on conditionally suitable sites unless there is reasonable assurance that, under the most critical anticipated subsidence conditions, housing units will not collapse, become unserviceable, or suffer structural damage requiring major repairs or replacement of structural elements, and that access roads, drainage systems and utilities can be maintained so that they will continue to function adequately. The recommendations in this section are intended to accomplish this purpose by reducing the vulnerability of buildings, roads and utilities to subsidence damage and by providing conditions which will reduce the difficulty of restoring any damage that may occur. The recommendations in this section are supplemented by recommended structural design requirements which would mitigate subsidence damage.

These recommendations do not apply if subsidence of the site or settlement of structures are prevented or minimized by other measures such as backfilling or deep foundations.

The quantitative information provided in this section and section 4 is intended to provide general guidance to the engineer. In each particular case, engineering judgment should be used and may result in modifications to these recommendations.

3.2 MONITORING SYSTEMS

Developers of conditionally suitable sites should consider, and HUD reserves the option to require, the installation of monitoring systems which can provide early warning of impending, or progressively increasing, subsidence. Such systems may use various techniques, ranging from visual surveillance or observation of settlement points to the installation of micro-seismic sensors, depending on specific site conditions.

3.3 PRECAUTIONS AGAINST MIGRATION OF SOILS INTO VOIDS OR FRACTURES

The following precautions should be taken if there is evidence of drained underground cavities:

(1) Drainage should be away from buildings. Underdrains and roof drains should be tied to closed stormwater systems or paved drainage swales;

(2) There should be no permanent ponds, leaching catch basins or other drainage facilities which increase seepage in the vicinity of any HUD insured building and preferably anywhere on the site;

(3) The drainage system should have adequate capacity to discharge the runoff from the 50-year rain storm without ponding and innundation of areas not designated as drainage swales;

(4) The discharge from the 5-year rain storm should be carried entirely by a closed drainage system or should be confined in concrete or asphalt lined drainage ditches;

(5) The site should be served by a sanitary sewer system, or special precautions should be taken to keep the percolation from sewage disposal systems within tolerable limits.

3.4 GRADING AND DRAINAGE

Gradients of landscaped areas and drainage swales should be designed for the intended drainage under the most critical anticipated subsidence conditions. Thus minimum required slopes should be increased and maximum allowable slopes decreased by amounts equal to the slope of the anticipated subsidence profile averaged over a 50 ft (15 m) length. Gradients away from building foundations should not be less than 2 percent. Any significant increase in the weight of overburden by regrading or construction should be avoided.

3.5 PIPELINES

3.5.1 Grades of Gravity Lines

Required minimum grades should be increased and allowable maximum grades decreased by the greater of the following grades: The slope of the anticipated subsidence profile, averaged over a 50 ft (15 m) length; or the slope attributable to the elevation difference caused by the subsidence settlement of any two successive manholes or catch basins.

3.5.2 Joints

Joints between adjacent pipe segments should be able to accommodate all translations and rotations resulting from the anticipated subsidence profile. Normally translational components of displacement are attributable to extensional or compressive ground strain. Rotational components of movement are attributable to the change in slope of the anticipated subsidence profile.

Locations where discontinuities in the subsidence profiles could develop, such as lines crossing known faults, should, if possible, be avoided. If such locations cannot be avoided, special designs, such as segments of flexible pipe, will be required.

Pressure lines should generally have telescopic joints to accommodate horizontal strains and swing joints (two successive 90° angles) to accommodate rotation between successive pipe segments. All joints should have positive restraints to prevent separation between successive pipe segments. Telescopic joints should provide for a total movement equal to or greater than 3 times the anticipated movement with adequate added clearance for rotation and should be installed with appropriate clearance between successive pipe segments. All flexible joints should be designed to resist the maximum pressures specified for the utility line without leakage. Adequacy of joints should be documented by reference to past performance or by proof testing.

Gas lines should generally be avoided in areas where severe subsidence is anticipated. If gas lines are used, swing joints as well as telescopic joints should be provided, and each house connection should have both types of joints at the main line connection and at the meter.

In gravity lines bell and spigot joints with O-rings or polyurethane fillers, and without restraint against separation, can be used to accommodate horizontal strains as well as rotations, however, in this case the required clearance should be doubled to provide for the case where movement attributable to the length of two pipe segments is concentrated in one single joint.

Flexible joints which can accommodate translation as well as rotation should be provided as close as possible to any building, manhole, catch basin, or other rigid structure to be connected.

3.5.3 Pipe Segments Between Joints

The length of pipe segments between joints should be such that the available clearance in each joint exceeds the anticipated translation and rotation attributable to the length of the pipe segment. These clearance requirements must be doubled for joints which provide no restraint against separation. In addition, each pipe segment should have adequate strength to resist tensile, compressive and bending forces resulting from the anticipated ground distortion between joints. Generally these forces increase as the length of the segment is increased and decrease when more flexible pipe is used. For pipelines larger than 3 in (80 mm) in diameter it is recommended that pipe segments not exceeding 8 ft (2.5 m) in length be used.

3.5.4 Bedding of Pipes

Pipes should be bedded to half their height in compacted granular material providing a base below the pipe of not less than 4 in (100 mm) or 1/6 times the outer pipe diameter, whichever is more, and backfilled to a depth of not less than 12 in (300 mm) above the pipe with selected material, free of lumps, and compacted in uniform 6-in (150 mm) layers. The rest of the trench should also be backfilled in uniform compacted layers. If concrete bedding is used it should be articulated at each joint, providing clearances at least equal to the joint clearance. Alternately, some other methods could be considered to alleviate subsidence effects, such as loose soil cushions in the immediate vicinity of the pipe or the "imperfect ditch method of construction" (see Ref. [2] page 93).2/

3.5.5 Check Valves

Check valves should be provided at appropriate locations in all gas and water mains to permit interruption of flow in case of subsidence-induced distress.

3.6 LANDSCAPING AND DRAINAGE STRUCTURES

3.6.1 General

Structures should either be strong enough to resist the forces induced by subsidence related ground strains and distortions, or flexible enough to accommodate the resulting deformations.

3.6.2 Manholes and Catch Basins

Manholes and catch basins should be steel reinforced and should have flexible joints at all the pipe connections.

3.6.3 Culverts

Concrete pipe culverts should be reinforced and should be segmented, jointed and bedded in accordance with the recommendations in section 3.5. Corrugated steel pipe does not normally require joints.

3.6.4 Retaining Walls

Concrete or masonry retaining walls should be steel reinforced and articulated by joints of adequate width at intervals not exceeding 30 ft (9 m). At least two number 5 bars should be provided along the upper and lower edges of all walls. Retaining walls which affect the stability of buildings should be defined in accordance with section 3.7.4.

3.6.5 Roads and Pavements

All roads and pavements should have minimum slopes of not less than 1/2 percent plus the slope of the anticipated subsidence profile, averaged over a 50 ft (15 m) length. Flexible (bituminous) pavement is recommended.

3.7 BUILDINGS

3.7.1 Size and Configuration of Buildings

Building units should preferably be one or two stories high and not exceed three stories unless all the anticipated subsidence effects are specifically considered in an engineering analysis. The plan dimension of buildings should generally be less than 80 ft (25 m) or 100 ft (30 m) across any diagonal. The lowest floor of buildings should preferably be on one plane and have a rectangular configuration (straight foundation walls).

3.7.2 Orientation of Buildings

To minimize the effects of ground strains, buildings should be oriented with the narrow dimension in the direction of the maximum anticipated subsidence slope.

2/ Numbers in brackets refer to literature references in section 5.

3.7.3 Separation of Buildings

To prevent bumping and minimize undesirable esthetic effects, buildings should be separated at least 6 ft (2 m). Breezeways or link structures between buildings should not exceed 12 ft (4 m) in width and there should be joints with adequate clearance between buildings and their link structures.

3.7.4 Structural Considerations

Buildings should either have adequate strength and stiffness to resist distortions and act as a rigid body or be flexible enough to accommodate anticipated displacements by elastic or inelastic deformations or by articulation and sliding joints. Structural elements such as walls, partitions and siding should preferably be flexible, even if a rigid foundation is provided. Added clearances should be provided in windows and doors in order to increase the tolerance to distortion.

3.7.5 Protection of Basement Walls and Foundation Elements

If ground compression is anticipated a protective layer of compressible backfill[3/] should be provided around basement walls and other deep foundation elements. This can be accomplished by incorporating a compressible layer in the backfill, or by excavating a narrow trench at a distance not exceeding 1/2 times the basement depth from the exterior face of the basement wall and backfilling the trench with compressible material.

[3/] Compressible materials are materials which have a stiffness much smaller than that of the surrounding soil.

4. BUILDING DESIGN AND CONSTRUCTION

4.1 APPLICABILITY

These recommendations apply to building construction on conditionally suitable sites and should be considered in addition to other applicable standards. In the interest of economy conditionally suitable sites are subdivided into two categories. Section 4.2 deals with sites where anticipated subsidence effects are moderate. Section 4.3 deals with severe subsidence conditions.

4.2 MINIMUM RECOMMENDATIONS

4.2.1 General

The recommendations in section 4.2 apply where anticipated horizontal ground strains do not exceed 0.1 percent, the length change in the foundation soil over the length of the building foundation in any direction does not exceed 1 in (250 mm), anticipated tilt does not exceed 1/200, the change in subsidence slope at the building site does not exceed 1/300 per 100 ft (30 m) length, and total settlement does not exceed 1 1/2 in (40 mm) in sands or 3 in (80 mm) in clays.

4.2.2 Foundation Walls

Foundation walls should be reinforced concrete construction or its equivalent in tensile strength. Minimum reinforcement should be two #5 bars provided near the bottom as well as near the top of the foundation wall.

4.2.3 Slabs on Grade

Slabs on grade should have a minimum thickness of 4 in (100 mm) at any point and should be reinforced in both directions. The following minimum reinforcement or its equivalent is suggested:

Maximum Length Between Joints	Required Reinforcement (welded wire fabric)
45 ft or less (14 m)	66 - 10/10
45 - 60 ft (14 m - 18 m)	66 - 8/8
60 - 75 ft (18 m - 22 m)	66 - 6/6

Slabs should be supported by at least 6 in (150 mm) of compacted sand and covered by a polyethylene sheet. The underside of slabs should be free of projections.

4.2.4 Masonry Construction

Masonry construction should have minimum steel reinforcement in accordance with the provisions for "partially reinforced masonry walls," ANSI Standard A41.2, section 9.10 [1]. Portland cement-lime mortar should be used.

4.2.5 Length of Buildings

Any single building or block of buildings should not exceed 80 ft (24 m) in length or 100 ft (30 m) across any diagonal, unless it is shown by an engineering analysis that the building can resist or accommodate anticipated subsidence effects.

4.2.6 Basement Walls

Basement walls should be designed to resist soil and hydrostatic pressures of not less than 100 psf per foot of depth of fill (5 kN/m^2 per m), or be protected against lateral pressure by a vertical layer of compressible material, placed without compaction.

4.2.7 Utility Connections

Flexible connections, capable of accommodating longitudinal translations as well as rotations should be provided immediately outside the foundation walls for all utility connections. All pressure lines should be provided with check valves and with positive restraints against separation.

4.2.8 Large Buildings

Buildings exceeding 3 stories in height or 80 ft (24 m) in length should be designed to resist or accommodate the anticipated subsidence effects. Their adequacy should be documented by an engineering analysis.

4.3 RECOMMENDATIONS FOR SEVERE SUBSIDENCE CONDITIONS

4.3.1 General

Recommendations in section 4.3 apply to all conditionally suitable sites where anticipated subsidence conditions are more severe than those defined in section 4.2. In all instances the minimum requirements in section 4.2 should be observed.

4.3.2 Recommended Design Criteria

4.3.2.1 General

Every building or other structure should be designed by a licensed structural engineer, with due consideration of the subsidence effects anticipated at the building site and in compliance with the recommendations in section 4.3.

4.3.2.2 Safety Margins

Buildings should be designed to resist all the loads stipulated in section 4.3.3 together with all other dead and live loads stipulated in the HUD Minimum Property Standards [6] with safety margins not less than those required in applicable standards. Drag forces and pressures acting on the foundation should be considered as live loads.

4.3.2.3 Joints

Joints and sliding connections should be designed to accommodate at least 2 times the anticipated translations, rotations and distortions. If displacements and rotations are concentrated in joints, esthetic effects should be considered. Undesirable visual effects should either be avoided by appropriate detailing, or plans should be prepared in advance for corrective measures such as jacking. All joints should provide restraints against vertical displacement between adjacent structural elements.

4.3.2.4 Tolerances for Tilt and Distortion

(1) Tilt

The maximum allowable tilt for buildings 3 stories or less in height should be 1 horizontal in 200 vertical. For buildings taller than 3 stories a maximum tilt of 1/500 is recommended.

(2) Distortions

For doors, windows and flexible structural systems such as wood frame or steel construction in-plane shear distortions smaller than 1/480 times the height need not be considered. Distortions between 1/480 times the height and 1/240 times the height should be considered in the design.

Larger distortions should be relieved by sliding joints and by special clearance in doors and windows. Distortion tolerances of masonry and concrete elements are very small. Thus deflection limits of foundations supporting masonry or concrete walls should not exceed those permitted in the HUD Minimum Property Standards, unless effects of distortions are relieved by appropriate joints.

4.3.2.5 Foundation Design

Foundations can be rigid or flexible. A rigid foundation should be designed to resist all the forces stipulated in sections 4.3.3.2 and 4.3.3.3 and those caused by the support conditions stipulated in section 4.3.3.4.1 and should not deflect more than 1/240 times its length nor more than the deflection tolerance of the superstructure. A flexible foundation should be designed to resist all the forces stipulated in sections 4.3.3.2, 4.3.3.3 and 4.3.3.4.2 and should not deflect more than 1/240 times its length, unless it can be demonstrated that a greater deflection tolerance is provided by a flexible or articulated superstructure.

If flexible foundations are designed as a series of rigid foundation segments connected by appropriate joints, each foundation segment should be designed as a rigid foundation. For very severe subsidence conditions rigid foundations designed in accordance with section 4.3.3.4.1 may not be adequate. In such instances, foundations should be either flexible with an appropriately articulated superstructure or designed to be independent of support conditions (supportable by any stable configuration of three reaction points) with provisions for corrective measures such as jacking to eliminate excessive tilt.

4.3.2.6 Interaction Between the Foundation and the Superstructure

Elements of the superstructure, such as walls, can be used to provide added stiffness to the foundation if the connection between these elements and the foundation is designed for composite action. The superstructure should be designed to resist all loads caused by foundation distortions which are not relieved by appropriate joints. The most critically affected elements will generally be wall elements such as piers and lintels. All piers and lintels should therefore be designed to resist in-plane shear and flexure and should be reinforced along their boundaries.

4.3.3 Design Loads

4.3.3.1 General

The design loads in this section can be either resisted or relieved by various measures. For instance, drag forces can be relieved by sliding supports, lateral pressures can be relieved by protective layers of compressible material, and effects of curvature can be relieved by articulation.

4.3.3.2 Drag Forces

Drag forces in tension or compression, caused by horizontal ground strain, should not be taken less than the following:

$$F_d = f(D + 0.5L)$$

where F_d = the drag force parallel to the direction of maximum ground strain,
f = the friction coefficient between the soil and the foundation,
D = design dead load,
L = design live load.

If no specific data are available $f = 1.25$ should be used. For foundations with a smooth underside free of projections, resting on a sand layer at least 6 in (150 mm) in thickness and covered by a polyethylene sheet, $f = 0.66$ can be used.

4.3.3.3 Lateral Soil Pressures

Passive soil pressures should be assumed to act on all vertical surfaces in contact with foundation soil. These pressures should be determined in accordance with established engineering practice but should not be taken less than 120 d (psf), where d is the depth below grade in feet [6 d (kN/m^2), where d is in meters] at any point.

4.3.3.4 Forces Caused by the Curvature of the Subsidence Profile

4.3.3.4.1 Rigid Foundations. Rigid foundations not exceeding 60 ft (18 m) in length should be designed to resist the shears and moments caused by the following support conditions:

(1) An unsupported length of 20 ft (6 m) or 0.67 ℓ, whichever is smaller anywhere within the foundation in the long, as well as the short direction of the building, where ℓ = length of the foundation in the direction under consideration.

(2) The following unsupported cantilevering lengths along the perimeter of the building:

(a) 8 ft (2.4 m) or (0.125 ℓ when 0.125 ℓ yields a length greater than 8 ft) if $\ell > 20$ ft (6 m)

(b) 0.4 ℓ if $\ell \leq 20$ ft (6 m)

Rigid foundations longer than 60 ft (18 m) and foundations for very severe subsidence conditions should either be designed to be independent of support conditions, or an analysis should be made in each case, considering anticipated curvature.

4.3.3.4.2 Flexible Foundations. Flexible foundations should be designed to resist the moments and shears resulting from the deflection curve caused by the curvature of the anticipated subsidence profile. If flexibility is achieved by articulation, foundation elements between joints will not be subjected to the moments and shears calculated for flexible foundations unless their length exceeds twice the critical length (ℓ_{cr}) as defined hereafter for tension zones, or ℓ_{cr} for compression zones.

A reasonable estimate of moments and shears in flexible foundations, induced by the ground curvature can be obtained from the following equations:[4/]

(1) Moments:

In the tension zone:

$$M = \frac{EI}{R}$$

$$R_{min} = 0.075 \frac{h^2}{S_{max}}$$

$$M_{max} = \frac{13.3\ EIS_{max}}{h^2}$$

where M = maximum moment in a given location in a subsidence area,
R = radius of curvature,
R_{min} = minimum radius of curvature in a given subsidence area, based on idealized conditions of a level ground surface and a level seam,
M_{max} = maximum moment in the most critical location in a given subsidence area, based on R_{min},
h = depth of seam below ground surface.

4/ See Appendix B for derivations. Note that equations may change when subsidence profile characteristics vary from those assumed.

In the compression zone:

$$M = 1.125 \frac{EI}{R}$$

$$M_{max} = \frac{15EIS_{max}}{h^2}$$

where S_{max} = maximum possible subsidence in a given subsidence area
E = Young's modulus of foundation element
I = Moment of inertia of foundation element
h = depth of seam below ground surface.

(2) Shear:

In the tension zone (zone of ground tension):

$$\overline{V} = 1.4\sqrt{\frac{EI\overline{w}}{R}}$$

$$\overline{V}_{max} = \frac{5.16}{h}\sqrt{EI\overline{w}S_{max}}$$

In the compression zone (zone of ground compression):

$$\overline{V} = 1.5\sqrt{\frac{EI\overline{w}}{R}}$$

$$V_{max} = \frac{5.5}{h}\sqrt{EI\overline{w}S_{max}}$$

where $\overline{V}$ = maximum shear in a given location
V_{max} = maximum shear in the most critical location, based on R_{min}
$\overline{w}$ = unit gravity load on foundation element
h = depth of seam below ground surface.

(3) Critical Length:

In the tension zone:

$$\ell_{cr} = \sqrt{\frac{2EI}{R\overline{w}}}$$

$$\ell_{cr(max)} = \frac{5.16}{h}\sqrt{\frac{EIS_{max}}{\overline{w}}}$$

In the compression zone:

$$\ell_{cr} = 2\sqrt{\frac{EI}{R\overline{w}}}$$

$$\ell_{cr(max)} = \frac{7.3}{h}\sqrt{\frac{EIS_{max}}{\overline{w}}}$$

where $\ell_{cr(max)}$ = critical length in the most critical location, based on R_{min}
ℓ_{cr} = critical length in a given location.

A foundation should be considered flexible if its length exceeds $2\ell_{cr}$ in a tension zone and ℓ_{cr} in a compression zone.

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APPENDIX A

Prediction of subsidence profile characteristics.

A.1 General

Much information is available internationally on subsidence prediction and subsidence profile characteristics. It must, however, be realized that methods which lead to reliable predictions under one set of geological conditions may not be reliable or even applicable under different conditions. All available methods, including the one following were developed for subsidence above active longwall mines. Although the subsidence profile that develops due to failure of pillars or mine floors in abandoned mines may sometimes resembles that above an active mine, there are no known methods that will predict eventual areal extent. The following methods should be used with care, and only by a qualified engineer.

A.2 Choice of Method

Unfortunately no systematic measurements have been carried out in various U.S. regions and it is thus ordinarily not possible to construct reliable mathematical models for guidance. Excellent general guidance for mathematical modeling can be derived from the Bureau of Mines Circulars IC8571 and IC8572 [3, 4]. More recent publications which provide a general overview of available information and extensive lists of references are two Appalachian Regional Commission reports: "Architectural Measures to Minimize Subsidence Damage" by Michael Baker, Jr., Inc. [2] and "State of the Art in Subsidence Control" by Gray and Gamble [8]. A very useful document which provides much practical information to designers is the "Subsidence Engineers Handbook" published in the U.K. by the National Coal Board (NCB) [9].

A comparison of the different mathematical models used indicates that any two different models which give similar results with respect to the settlement, may give very different results for curvatures, strains and slopes. Since the latter parameters are the more critical, the design is very sensitive to the mathematical model used. This point is illustrated in figure A.1. In this figure the ratio of length of structure, ℓ, to the depth of seam below the surface (h) is plotted against the ratio of settlement, s, to the maximum settlement, S. For any specific location, particularly from the inflection point of the profiles toward the maximum settlement, the total settlements calculated by any two of these four curves may not differ significantly. However, the curvature will vary significantly. For instance, the minimum radius of curvature, calculated from the NCB curve is approximately $0.077\ h^2/s$. For the Donets coal field, where the settlements are quite close to those predicted by the NCB curve, the minimum radius is approximately $0.172\ h^2/s$ or 2.2 times that calculated from the NCB profile, and predicted horizontal strain would be approximately 67 percent of the strain in the NCB model. A comparison of the different published models indicates that for the sake of predicting the critical parameters of strain, curvature and slope the NCB model tends to give conservative results. Since this model is also empirically based and has been developed from a substantial amount of carefully compiled data, it is recommended that in absence of specific and reliable information, strains, slopes and curvatures should not be taken less than those calculated in accordance with the NCB handbook. All quantitative data in appendix A as well as in the provisions in section 4 of this report were developed accordingly.

A.3 Mathematical Modeling

The NCB handbook presents graphical information which can be used directly to develop subsidence profiles. The National Coal Board also developed computer programs on their data.

In complex cases, or when large areas have to be evaluated, mathematical modeling may be desirable. Bräuner [3] discusses various modeling techniques that could be used. The following principles should be kept in mind:

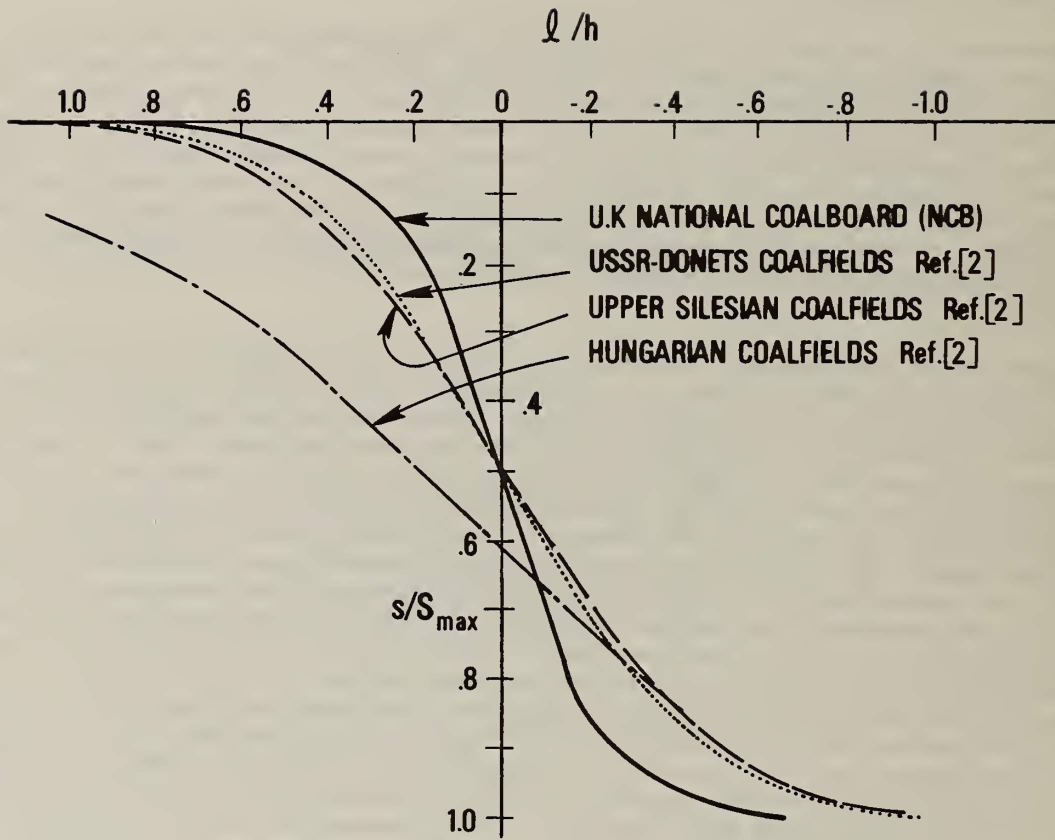

FIGURE A.I MISCELLANEOUS SUBSIDENCE PROFILES

(1) The model should not underestimate the critical parameters of slope and curvature.

(2) The extent of the affected area and the position of points of maximum curvature and slope should be approximately predicted.

Modeling is generally based on the premise that superposition can be used to integrate the influence of increments of mined areas. For superposition to be valid, a surface point over the edge of a semi-infinite mined area should experience exactly 1/2 the maximum subsidence (exactly 1/2 the area is contributing to the subsidence of the point). Since this is normally not the case (the point s = 0.5 S is normally located over the mined area and not over its boundary) mathematical models are not accurate and compensating corrections have to be made to approximately locate points of critical slopes or curvature.

Approximate models could be developed for any particular area. For the purpose of this appendix the following profile function was derived using methods from Ref. [3]. The intent here is to provide a modeling tool which will yield profiles that are similar to the NCB profiles:

$$s_{(x/h)} = \frac{S_{max}}{6}\left[3 - \text{erf}\left(6.516\,\frac{x}{h}\right) - 2\,\text{erf}\,3.258\,\frac{x}{h}\right] \qquad \text{eq. (1)}$$

where s = subsidence at any point

S_{max} = maximum possible subsidence

$\frac{x}{h}$ = horizontal distance divided by the depth of the seam below the surface (nondimensional)

erf = error function, $\text{erf}(z) = \frac{2}{\pi}\int_0^z e^{-t^2}\,dt$

Point x/h = 0 occurs at the inflection point where $s = 0.5\ S_{max}$. x/h is positive away from the subsidence trough and negative toward its center. The function is antisymmetric about x/h = 0, and asymptotic to the lines s = 0 and $s = S_{max}$ (thus reasonable cutoff points must be assumed).

From the profile function in eq. (1) the following influence function can be derived:

$$p = 4.5\,\frac{S_{max}}{h^2}\left\{\exp\left[-42.463\left(\frac{r}{h}\right)^2\right] + 0.5\exp\left[-10.616\left(\frac{r}{h}\right)^2\right]\right\} \qquad \text{eq. (2)}$$

The subsidence at any point P, tributary to an incremental mined area dA will be pdA where p(r) is evaluated for the appropriate distance r, which is a horizontal projection of the radial distance from P to dA. Thus at any point P:

$$ds = p(r)\,dA$$

$$\text{and } s = \iint_A p(r)\,dA$$

$$\text{Thus } S_{max} = 2\pi\int_0^\infty rp\,dr$$

A half plot of the profile function is shown in figure A.2 together with the NCB profile. It should be noted that while the curves are reasonably close there are several important discrepancies:

(1) The maximum slope of the NCB curve is $2.75\ S_{max}/h$. Equation (1) has a maximum slope of $2.45\ S_{max}/h$.

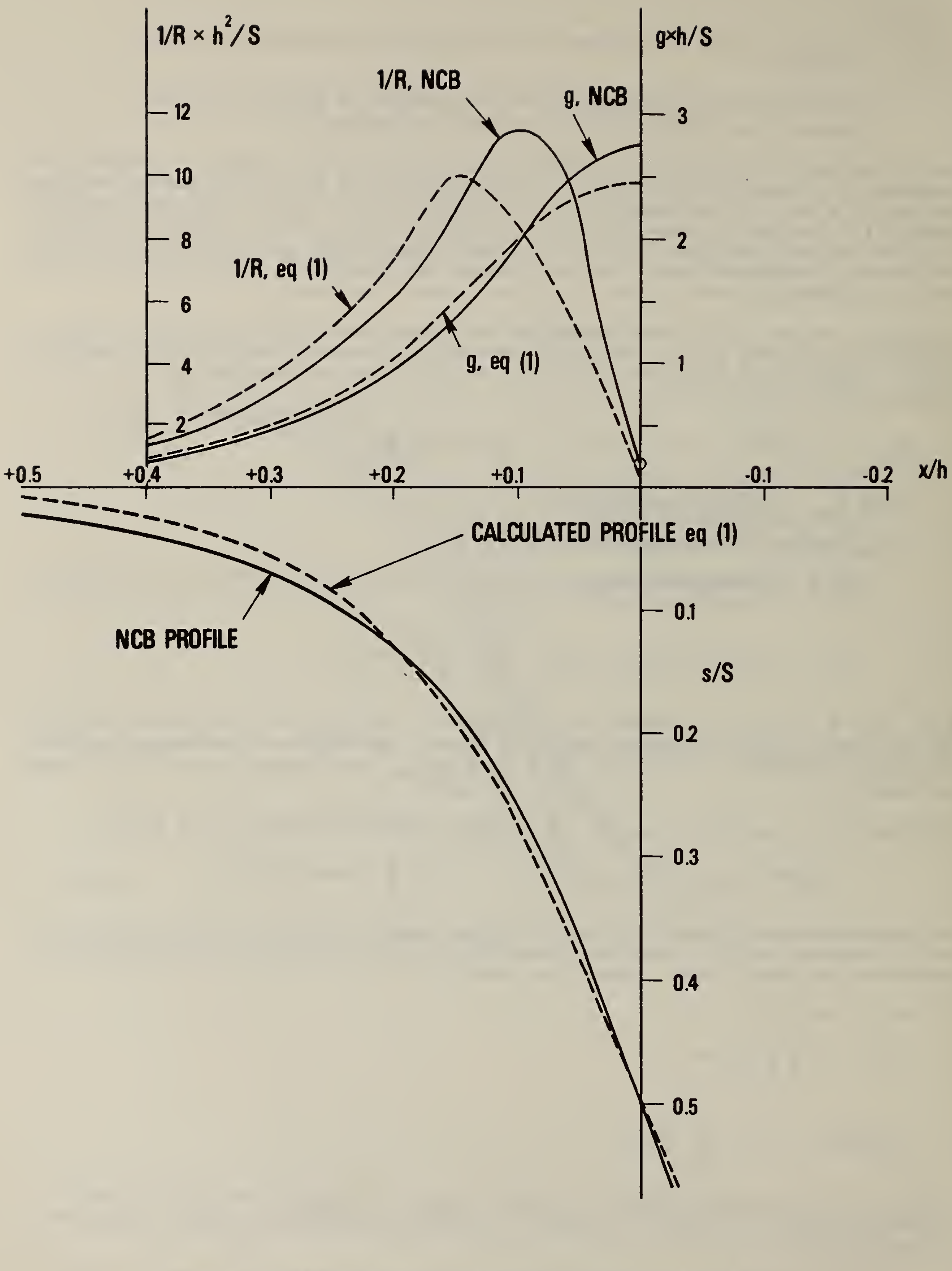

FIGURE A.2 COMPARISON OF NCB CURVE WITH PROFILE FUNCTION

(2) The locations of maximum strain and curvature do not exactly coincide.

(3) The profile function underestimates settlements in the fringe area. This discrepancy is significant where $x/h > 0.3$.

Some compensatory corrections are recommended. Figure A.2 shows a comparison of slopes and curvatures. The following information can be derived from the figure:

> Critical slopes derived from the profile function should be increased by 12 percent; curvatures should be increased by 15 percent; strains should be increased by 8 percent; settlements in fringe areas should be doubled.

Another adjustment is needed to correct the position of point $x/h = 0$. One method suggested by Brauner [3] is to subtract a strip of width $x = d$ from the mined panel before the integration is performed, where d is the distance from the inflection point to a point above the edge of the mined panel. For the NCB profile $d/h = 0.14$. Such a correction is recommended but only if $w \geq h$.

The influence function p is plotted in figure A.3. Note that if $r > 0.5$ h mined area increments would have no significant influence on the settlement of the point.

The influence function could be used for any combination of mined seams using an appropriate percentage of the depth of the seam to calculate S_{max} (as discussed in the next section), and could be programmed to calculate subsidence patterns of large areas using finite elements of mined seams.

A.4 Subsidence Profile Parameters

The significant parameters for any given subsidence profile (not in order of importance) are:

(1) The settlement
(2) The horizontal displacement
(3) The slope
(4) The curvature
(5) The horizontal strain

These parameters are briefly discussed hereafter.

(1) Settlement (s, S, S_{max})

(a) Significance

Settlement per se does not necessarily damage structures if it is uniform over an area or if it causes rigid body tilt without distortion. Thus points of maximum settlement are not necessarily critical with respect to structural damage. Experience, however, indicates that there is always a certain amount of differential settlement associated with overall settlements. The following correlations between total and differential settlement have been observed [7]:

for sands: $\Delta s/\ell = \frac{S}{600}$

for clays: $\Delta s/\ell = \frac{S}{1250}$

where $\Delta s/\ell$ = differential settlement
S = total settlement
ℓ = horizontal distance between two points of observed settlement.

Since it also has been observed that serious damage will result when $\Delta s/\ell > 1/300$, serious damage to unprotected structures may result from total settlements exceeding 2 in (5 cm) in sands or 4 in (10 cm) in clays.

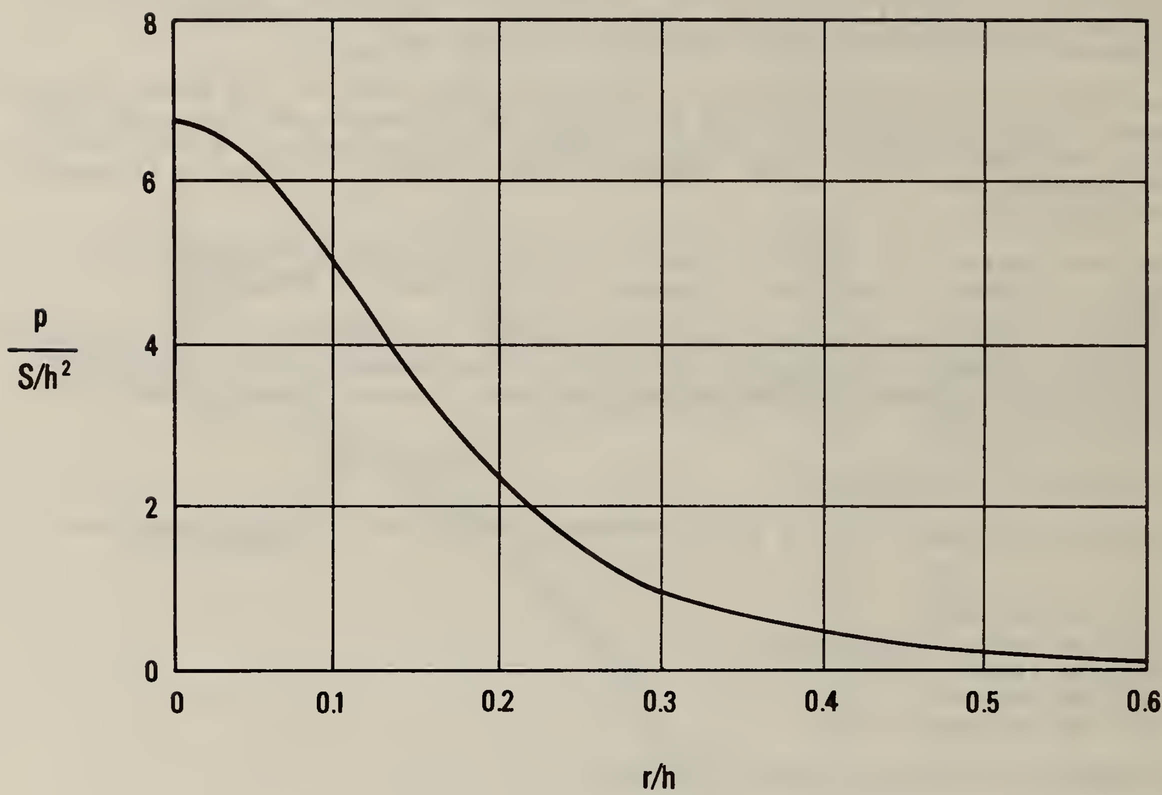

FIGURE A.3 INFLUENCE FUNCTION p

When effects of settlements are assessed it is necesary to consider utilities and their connections, as well as drainage patterns.

(b) Characteristics

The surface settlement caused by a mined panel is dish shaped and affects an area which is substantially greater than the plan dimension of the panel. The maximum settlement occurs in an area which includes the center of the dish. The magnitude of the maximum settlement in a subsidence area is approximately predictable and can be expressed by the following equation:

$$S = f_1(am) = f_1 S_{max} \qquad \text{eq. (3)}$$

Settlements of individual points are more difficult to predict. Generally, settlement at a specific location is a function of the maximum settlement. Thus:

$$s = f_2(S) \qquad \text{eq. (4)}$$

Note that s = settlement at any point

S = maximum settlement in a given subsidence area

S_{max} = maximum possible settlement

a = a constant, depending on mining methods (storing of wastes)

m = thickness of mined seam

Function f_1 is plotted in figure A.4, which was developed from the NCB profile. In the figure it is assumed that there is a rectangular mined panel with a length equal to or greater than 1.4 h. As the width of the panel increases from 0 to 1.4 h, S increases from 0 to S_{max}. For comparison, function f_1 was also derived from the influence coefficient p in eq. (2). Note that the curve derived from eq. (2) would somewhat overestimate settlements caused by narrow panels. The plot in figure A.4 implies that for a panel of width w = 1.4 h, S would reach S_{max} in the center. For larger panels there would be a larger area in the center where $S = S_{max}$. The width at which S becomes S_{max} is sometimes referred to as the "critical" width.

Constant "a" varies for various areas and mining methods. It is sensitive to the method of storing of mine wastes. Internationally a range of values from a = 0.12 to a = 1.0 has been reported. Measurements in Pennsylvania indicate values from 0.5 to 0.6, and in Arizona copper mines from 0.7 to 1.0 [2]. Function f_2 is the profile function which has been previously discussed. It can be derived from the NCB curve or from eq. (1). Figure A.5 shows a plot of the NCB profile function. It should be noted that the plots in figures A.2 and A.5 are for fully developed profiles, level ground and a level seam. If the mined width is subcritical or if the seam is inclined relative to the ground surface, adjustements have to be made. In simple cases this is most easily accomplished by the methods presented in the Subsidence Engineers Handbook [9]. In more complex cases, profiles could be developed from influence function p or by other mathematical models.

(2) Horizontal Displacement (v, V, V_{max})

(a) Significance

Normally, horizontal strains rather than displacements are recognized as significant parameters with respect to subsidence damage. However, an appreciation of the magnitude of anticipated horizontal displacement is often important. This is particularly true in the case of long structures where the relative displacement between two distant points needs to be considered by the designer.

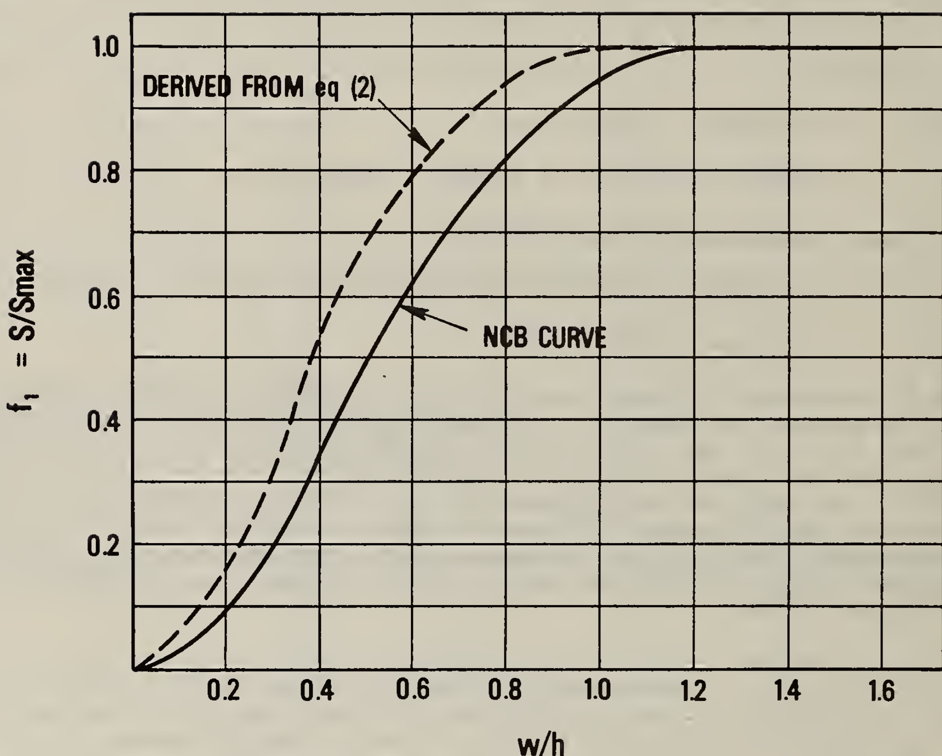

FIGURE A.4 PLOT OF FUNCTION f_1

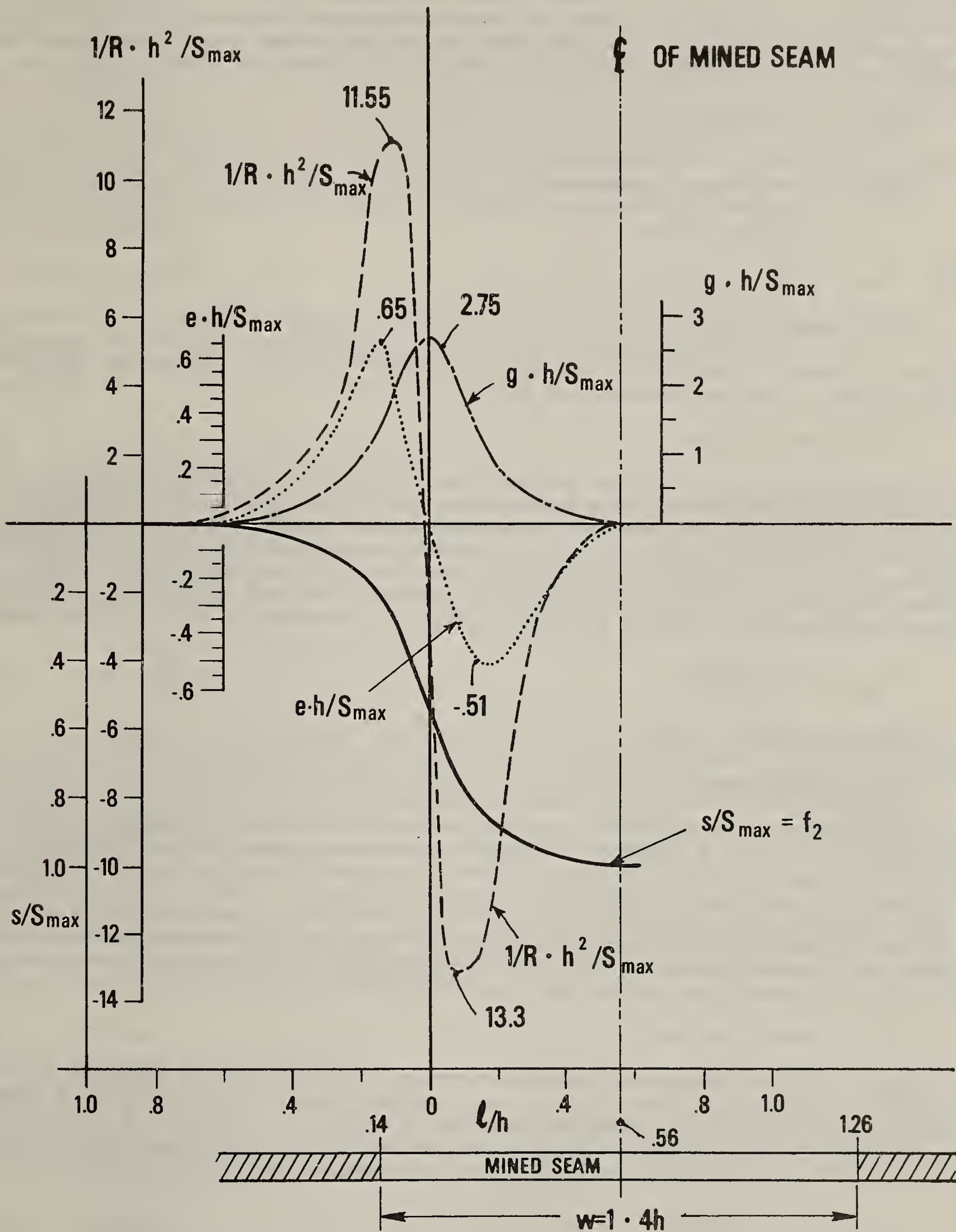

FIGURE A.5 SUBSIDENCE PROFILE CHARACTERISTICS

(b) Characteristics

Typical magnitudes of maximum horizontal displacements (V) were listed by Brauner [3, pg. 31] and generally range from 0.16 S to 0.45 S. A typical value most often encountered is 0.3 S. The horizontal displacement is inward (toward the center of the trough) and has been observed to be directly proportional to slope. Figure A.5 shows a nondimensional plot of the slope (curve g h/s). A reasonable estimate of the horizontal displacement v at any point could thus be obtained by assuming that V = 0.3 S and, $v/V \propto g/G$.

$$\text{thus } v = 0.3\ S \times \frac{g}{G}$$

where v = horizontal displacement
g = slope
G = maximum slope

(3) Slope (g, G, G_{max})

(a) Significance

Slope is primarily significant as a measure of rigid-body tilt. Slopes can also cause disruptions in drainage patterns and gravity pipelines.

(b) Characteristics

A non-dimensional plot of slopes derived from NCB profile is shown in figure A.5. In figure A.2 a nondimensional plot derived from eq. (1) is compared with the NCB plot. Note that the inflection point of the subsidence curve is also the point of maximum slope. In the nondimensional length scale this point is marked as $x/h = 0$ (or $\ell/h = 0$). This approach has been adopted since this is a convenient reference point which is more or less fixed relative to the critical locations of maximum strain and curvature. In accordance with the NCB data the maximum possible slope can be estimated by the following relationship:

$$G_{max} = 2.75 \frac{S_{max}}{h}$$

(4) Curvature (1/R)

(a) Signficance

While a uniform settlement or tilt may not subject a structure to significant loads, curvature will cause a structure to deflect or distort and thus always cause loads. Since strain is proportional to curvature, and thus strain and curvature occur simultaneously, curvature is not always recognized as a separate parameter. Thus the NCB handbook states its structural design criteria in terms of horizontal strain which implicitly contains some effects of curvature. In the criteria and provisions in this document curvature is recognized as a separate parameter, since it is deemed important to evaluate effects of curvature on flexible foundations, joints, and pipe connections.

(b) Characteristics

Curvature, or its inverse the radius of curvature, changes over the length of the subsidence profile. Curvature is zero at the point of maximum slope. Figure A.5 shows a nondimensional plot of curvature, developed from the NCB profile. In figure A.2 this plot is compared with a plot of curvature derived from the profile function in eq. (1). In accordance with the NCB data, maximum curvature can be estimated by the following equation:

$$\frac{1}{R_{min}} = 13.3 \frac{S_{max}}{h^2}$$

(5) Horizontal Strain ($\pm e$, $\pm E$, $\pm E_{max}$)

(a) Significance

Horizontal strain is the most important parameter in structural design, since horizontal strains of damaging magnitudes may be associated with curvatures which are not severe enough to be critical. Figure A.6 shows empirical relationships between horizontal strains and structural damage taken from Ref. [9]. Damage levels may, however be different for different construction technologies. Tensile as well as compressive strains must be considered in building design. In addition to traction forces on building foundations, compressive strains may also cause very high lateral pressures on retaining walls and foundations, which under extreme conditions may approach the passive earth pressure in magnitude. Buckling of pavements and thin slabs caused by compressive strains is a possibility which should be taken into consideration.

(b) Characteristics

A nondimensional plot of strains based on the NCB profile is shown in figure A.5. The NCB handbook reports the following relationship between strain and curvature:

$$e = \sqrt{\frac{0.08}{R}}$$

where R is in feet. (1 ft = 0.3048 m)

Implicit in this relationship is the premise that strain is proportional to $1/\sqrt{\ell}$. This raises some questions, since elsewhere in the NCB manual maximum possible strains are calculated by the following nondimensional equation:

$$+E_{max} = 0.65\,\frac{S_{max}}{h}$$

$$-E_{max} = 0.51\,\frac{S_{max}}{h}$$

For subcritical profiles where $S < S_{max}$, this relationship will change. Figure A.7 shows values of $+E$, $-E$ and G for various w/h ratios, developed from the NCB data. These same data are presented in the NCB handbook in terms of S/h, where S has to be evaluated first as a function of w/h. In figure A.7 the data are shown in terms of S_{max}/h, so that their absolute value can be compared. Note that only the compressive strain may be more severe in a subcritical profile, with a maximum value of 0.675 S_{max}/h at w/h = 0.5.

A.5 Summary

(1) It is recommended that in the absence of specific and reliable data, maximum values for horizontal displacement, slope, curvature and strain shall not be taken less than the following values, derived from the NCB profiles:

$$V_{max} = 0.3\,S_{max}$$

$$G_{max} = 2.75\,\frac{S_{max}}{h}$$

$$+E_{max} = 0.65\,\frac{S_{max}}{h}$$

$$-E_{max} = 0.51\,\frac{S_{max}}{h}$$

$$\frac{1}{R_{min}} = 13.3\,\frac{S_{max}}{h^2}$$

where S_{max} = am

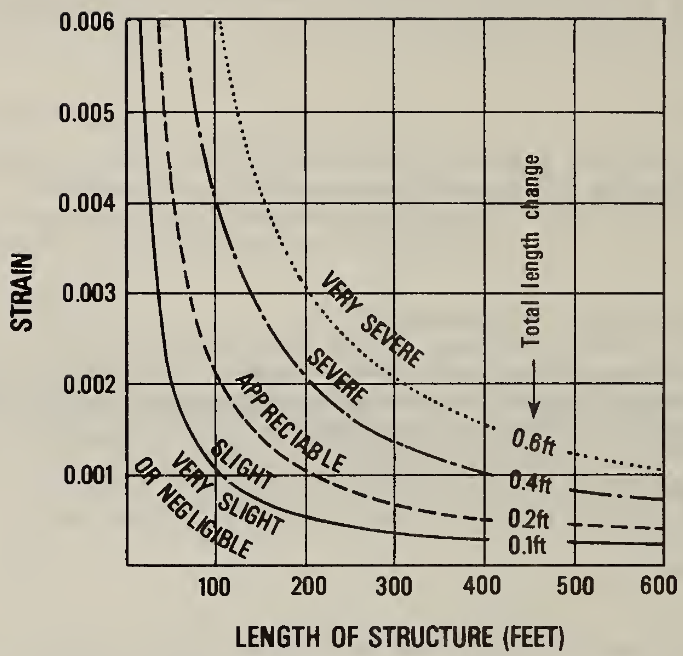

FIGURE A.6 EMPIRICAL RELATIONSHIP BETWEEN STRAIN AND STRUCTURAL DAMAGE TAKEN FROM REFERENCE (9)

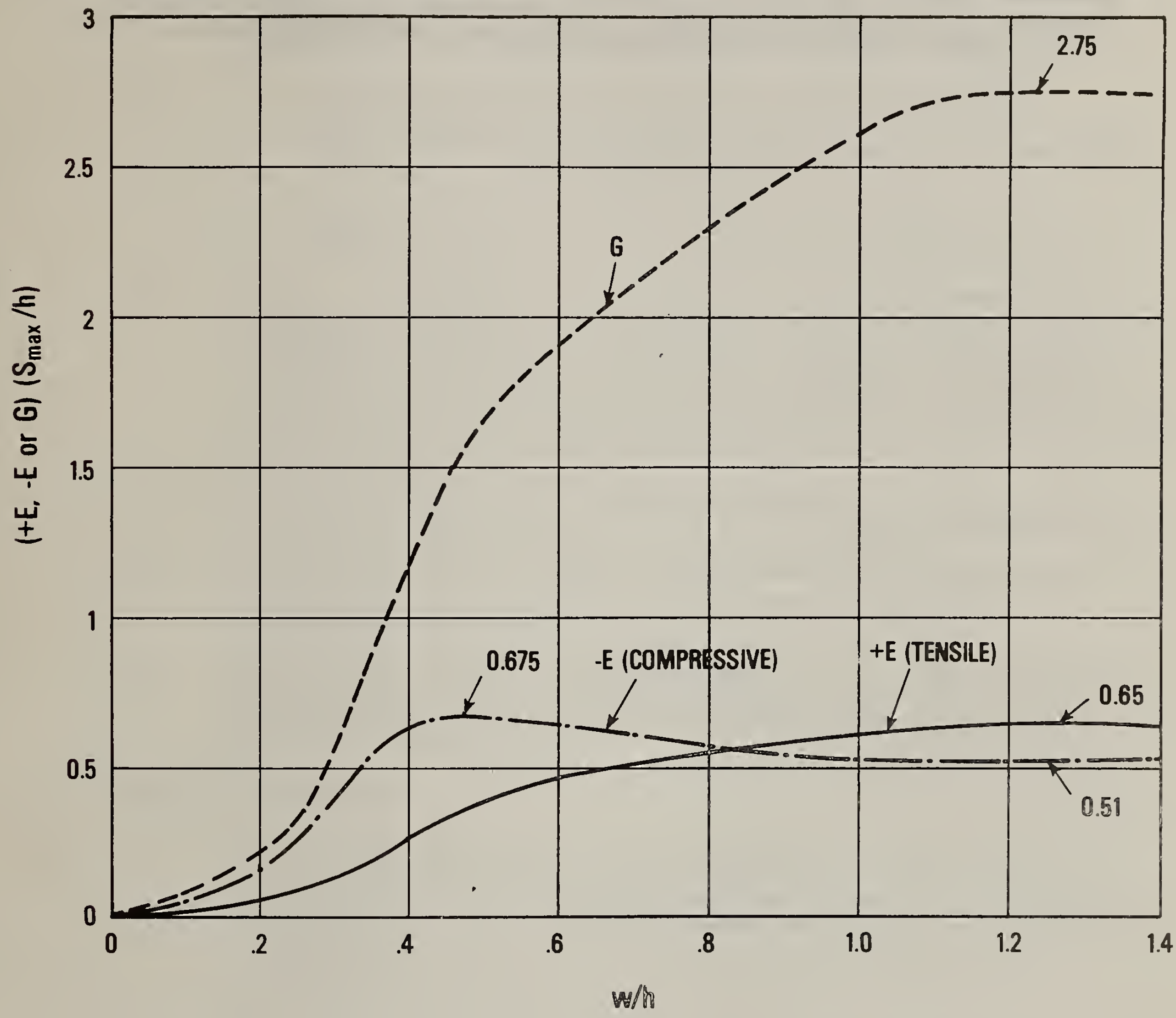

FIGURE A.7 MAXIMUM VALUES OF SLOPE AND STRAINS FOR CRITICAL AND SUBCRITICAL PROFILES

Values for the constant "a" range from 0.5 to 0.6 in Pennsylvania and from 0.7 to 1.0 in Arizona copper mines. In absence of any other information, a = 0.9 should be used.

(2) Subsidence profiles can be reasonably derived by mathematical modeling using eq. (1) and eq. (2).

(3) Subsidence profile characteristics for fully developed profiles and level seams and ground are shown in figure A.5. Modifications for inclined seams can be made in accordance with the NCB methods (Ref. [9]) or by mathematical modeling using eqs. (1) and (2). Modifications for subcritical profiles can be made using figures A.4 and A.7.

APPENDIX B - COMMENTARY

B.1 General

The intent of the commentary is to provide clarification where needed. Thus only some of the sections are discussed.

B.2 Commentary on Section 2

2.5.1 In general, a probabilistic risk assessment cannot be realistically accomplished. Thus a deterministic two-step approach was adopted.

2.5.4.1 (1) The threshold for horizontal strain is based on information published by the U.K. National Coal Board [9] (see also figure A.6) and on limitations used in other countries (see for instance, Ref. [2]), pg. 67 - France, Germany, Japan).

(2) The length change limitation is based on the information in figure A.6.

2.5.4.3 Option 2. An example of protective legislation is the Commonwealth of Pennsylvania Bituminous Mine Subsidence and Land Conservation Act of 1966 whereby the opportunity to purchase pillar support is offered to the homeowner. In addition to this protective legislation the Commonwealth of Pennsylvania also offers mine subsidence insurance. The combined effect of the protective measures and the insurance would in most instances reduce the risk to HUD to an acceptable level.

Protective measures such as harmonic extraction or backfilling are discussed by Woodroff, Vol. 2, p. 116 [12] and by Gray and Gamble [8].

2.6 Not all the information items listed are necessarily required or even obtainable in every instance. Thus the concept of "pertinent" information is introduced.

2.6.6 The existence of faults could cause discontinuities in the subsidence profile. In this case the relationships between the geometry of the mined area and the subsidence profile characteristics discussed in appendix A would not apply.

B.3 Commentary on Section 3.

3.1 The term "most critical anticipated conditions" is used in accordance with the methodology discussed under section 2.5. "Most critical" thus means that once it has been established that subsidence can reasonably be expected to occur, it should be assumed that the pattern of subsidence will be the most unfavorable for the structure or utility under consideration.

The recommendations fall into three categories.

(1) Those which will strengthen the resistance to damage (i.e., reinforcement).

(2) Those which reduce the likelihood of occurrence of damage (i.e., orientation of buildings).

(3) Those which will make remedial measures feasible (i.e., excess slopes in pipelines).

3.2 Monitoring systems may be particularly useful before construction is completed since preventive measures could be taken in advance, and also because long-term observations are usually much more effective than a short-term site investigation.

3.5.2 Positive joint restraints are required for pressure lines because of the serious consequences of joint separation. The minimum travel in a joint that must accommodate elongation as well as shortening would have to be at least 2 times the calculated movement (the movement of 2 pipe lengths may be concentrated in 1 joint) with an installation clearance between pipes of at least 1 times the calculated movement. The required clearance of 3 times the calculated movement provides a reasonable margin for tolerance, errors and unforeseen events.

3.5.3 It is reasoned that when there are joint restraints all joints will be effective in accommodating movement. If there are no restraints, the relative movement between pipe segments could in some instances occur in alternate joints. Thus twice the required clearance should be available. Recommended maximum lengths of pipe segments are based on recommendations in Reference [11]. Small diameter pipes are exempted because of their flexibility.

3.6.4 The articulation at 30 ft (9 m) intervals is intended to prevent the build up of excessive restraint forces.

3.7 These recommendations are general in nature. More specific recommendations are given in section 4.

3.7.1 Size limitations are intended to minimize effects of ground strains. For a 100 ft (30 m) length of buildings a 0.001 strain will not cause substantial damage (see figure A.6). Thus no special engineering analysis would be required unless the building is longer or the strain exceeds 0.001, a strain level which would be associated with "severe" subsidence conditions as defined in section 4.3, and would thus require engineering analysis for any size of building.

3.7.2 Orientation: This approach was proposed in Ref. [10]. The proposed orientation would subject the building to the least damaging conditions, since the shortest dimension would be oriented in the direction of maximum strain.

3.7.4 Flexible structural systems are recommended. This recommendation covers also non-loadbearing elements such as veneer and partitions. Brick veneer should be avoided. Flexible structural systems, such as wood frame construction with dry wall partitions are able to accommodate substantial distortions without significant damage.

3.7.5 Uncompacted compressible backfill, such as slag, has been successfully used in British mine subsidence areas [9].

B.4 Commentary on Section 4

4.2 It is desirable in the interest of economy to distinguish between moderate and severe subsidence since minor modifications in construction can adequately protect buildings in areas where only moderate subsidence settlements are expected.

4.2.1 The threshold for moderate subsidence is set at a strain of either 0.001 or a length change in the ground over the length of any foundation of less than 1 in. Thus if a building is longer than 100 ft (30 m) the maximum allowable strain would be reduced. In figure A.6 this threshold falls in the zone of "very slight damage." The 1/200 tilt is also not considered disruptive in small buildings. The limits for total settlement and curvature are based on information from Ref. [7], where it was shown that total settlements exceeding 2 in (50 m) in sands or 4 in (100 mm) in clays would probably be associated with damaging differential settlements.

4.2.2 The required reinforcement in foundation walls is designed to provide flexural strength which would permit the foundation to span areas of reduced or lost support.

4.2.3 Slabs equivalent to the Type II slab recommended by the Building Research Advisory Board [5] are required. These slabs are able to resist moderate traction forces resulting from horizontal ground strain by resisting the frictional force induced by their own weight.

4.2.4 ANSI Standard A.41.2 calls for reinforcement along the boundaries of shear walls and around openings, or at 8 ft (2.5 m) spacing. While this partial reinforcement is probably not very effective in resisting in-plane shear, it will greatly increase the resistance of walls to in-plane bending, and thus enable walls to span over zones of reduced foundation support. The reinforcement around openings will help prevent crack formations at re-entrent corners and will increase in-plane bending resistance of piers and lintels.

The intent of the requirement for portland-cement-lime mortar is to exclude the use of masonry cement from mine subsidence areas. This will insure better quality control in mortars, decrease the variability in tensile strength, and increase flexibility.

4.2.6 Compressive ground strains will cause increased lateral pressures. An allowance is therefore made for a moderate increase in lateral pressures.

4.3 The most important difference between the minimum recommendations in section 4.2 and the criteria in this section is the statement in section 4.3 that all buildings should be designed by a licensed professional engineer. For this reason section 4.3 contains design criteria, while the recommendations in section 4.2 are prescriptive. Since in some instances design calculalations based on section 4.3 may indicate that reinforcement requirements are less than those recommendations in section 4.2 the statement was added that in all instances the minimum recommendations in section 4.2 should be observed.

4.3.2.2 Since in ultimate load design for concrete different load factors are used for dead and live loads, all forces caused by subsidence were defined as live loads.

4.3.2.3 This recommendation is similar to that for pipe joints which was discussed under section 3.5.2.

4.3.2.4 Unfortunately there is not much reliable information on distortion tolerances. Tests on a full scale wood frame house indicate that actual distortions experienced by buildings in service conditions are very small [14]. Some racking tests to failure indicate tolerances greater than $\ell/250$ for let-in bracing and plywood sheathing, but lesser tolerances for gypsum board [10]. A racking test on a prefabricated wood frame module also indicates tolerances of the order of $\ell/250$ [13]. It should be recognized that a wood-frame house would actually accommodate much more distortion than an individual panel because of joint flexibility.

4.3.2.5 "Rigid foundation design" as specified in section 4.3.3.4.1 is intended for severe, but not for the extreme condition where jacking would be required to correct subsidence effects. For this extreme condition a rigid foundation would have to be designed which is completely independent of support conditions and which resists moments, shear and torsions greater than those resulting from the loading conditions in 4.3.3.4.1.

4.3.2.6 It is reasonable to take advantage of basement or other walls to stiffen rigid foundations, provided that the connection between the walls and the foundation is designed to resist the horizontal shear resulting from composite action. Actual loads on piers and lintels may be difficult to calculate. It is therefore recommended that all such elements should be reinforced along their boundaries.

4.3.3.2 The drag forces act on the underside of foundations. Thus, induced axial forces as well as moments should be considered. The use of a friction factor of 1.25 and 1/2 the design live load should result in conservative design.

4.3.3.3 Lateral pressures could also be relieved by uncompacted compressible backfill.

4.3.3.4.1 The criteria for rigid foundations follow the recommendations by the Building Research Advisory Board [5]. The criteria would not necessarily result in adequate design for long foundations or for very severe curvature, since the unsupported span length considered in accordance with section 4.3.3.4.1 may not be adequate.

4.3.3.4.2 The derivation for moments and shears in flexible foundations are based on the following premises:

(1) The curvature-induced moment that can occur anywhere in a flexible foundation is given by the following equation:

$$M = EI\frac{d^2y}{dx^2} \simeq \frac{EI}{R}$$

where x = distance in the horizontal direction
y = distance in the vertical direction
EI = cross section stiffness of the foundation
R = radius of curvature.

(2) The maximum curvature-induced shear will occur when the elastic subgrade reaction becomes very large. Thus shear derived on the basis of the simplifying assumption of an infinitely stiff subgrade will be the upper bound for the shear that can develop under any specific set of conditions, and can therefore be used for design. This simplification is justified by the fact that elastic subgrade reactions are difficult to determine, and that a more sophisticated approach is not warranted because of the considerable uncertainty associated with the determination of curvature.

Two cases are considered: Tensile ground strain, shown in figure B.1.(a) and compressive ground strain, shown in figure B.1(b).

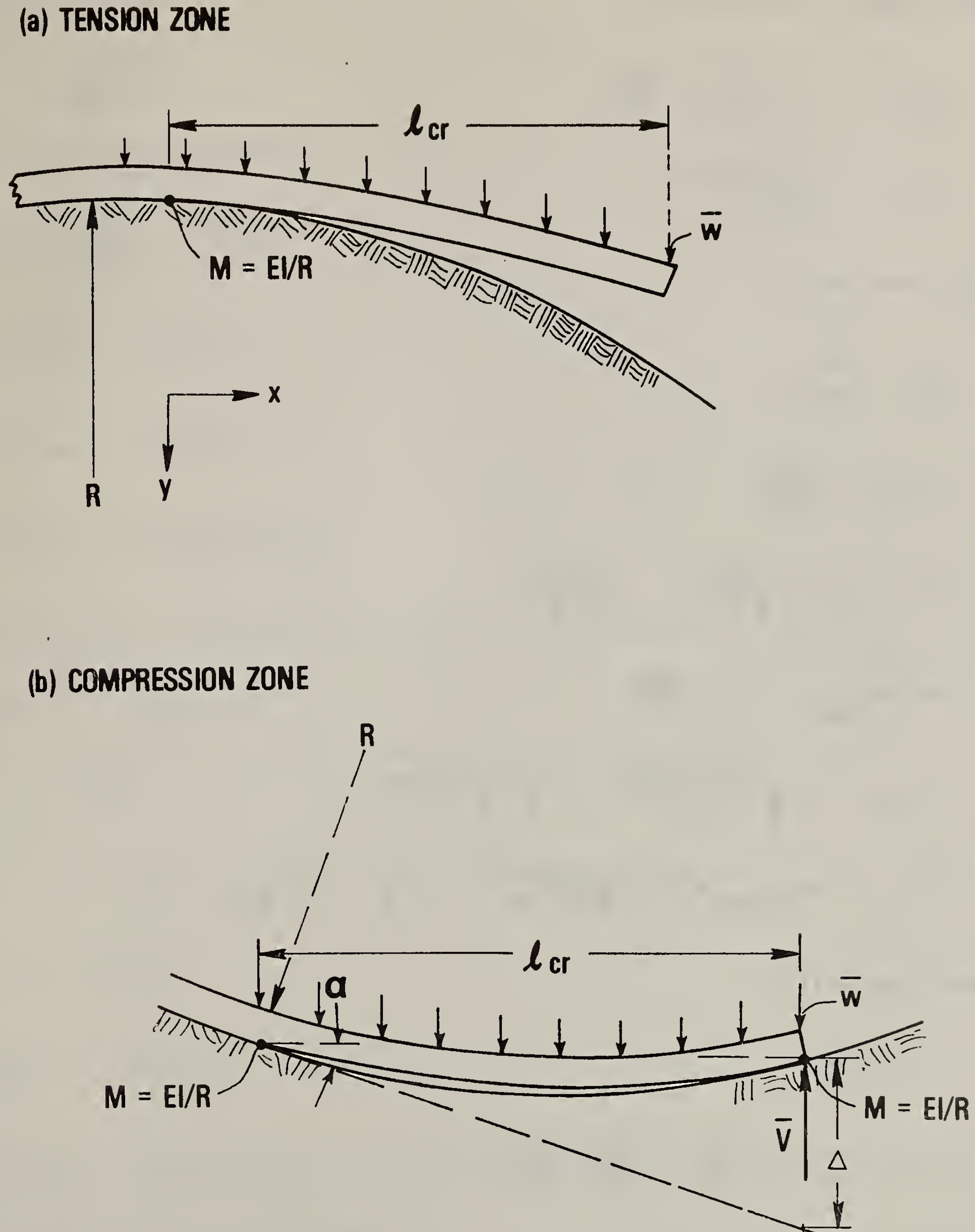

FIGURE B.1 ASSUMED IDEALIZED SUPPORT CONDITIONS FOR FLEXIBLE FOUNDATIONS

From figure A.5 (NCB profile):

$$\frac{1}{R_{min}} = 13.3\,\frac{S_{max}}{h^2} = \frac{M_{max}}{EI}$$

$$M_{max} = \frac{13.3\ EIS_{max}}{h^2}$$

From figure B.1 (a)

$$\frac{EI}{R} = \frac{\overline{w}\ell^2_{cr}}{2}$$

$$\therefore\ \ell_{cr} = \sqrt{\frac{2EI}{R\overline{w}}}$$

$$\overline{V} = \overline{w}\ell_{cr} = \sqrt{\frac{2EI\overline{w}}{R}} \simeq 1.4\sqrt{\frac{EI\overline{w}}{R}}$$

$$\text{since } \frac{1}{R_{min}} = 13.3\,\frac{S_{max}}{h^2}\ ,$$

$$\ell_{cr(max)} = \sqrt{\frac{26.6\ EIS_{max}}{\overline{w}h^2}} = \frac{5.16}{h}\sqrt{\frac{EIS_{max}}{\overline{w}}}$$

$$\overline{V}_{max} = \overline{w}\ell_{cr(max)} = \frac{5.16}{h}\sqrt{EI\overline{w}S_{max}}\ .$$

From figure B.1(b):

$$\alpha = \frac{\ell_{cr}}{2R}$$

$$\Delta = \ell_{cr}\,\alpha = \frac{\ell^2_{cr}}{2R} = \frac{\overline{V}\ell^3_{cr}}{3EI} - \frac{\overline{w}\ell^4_{cr}}{8EI}$$

$$\left.\begin{aligned}\frac{\overline{V}\ell_{cr}}{3EI} - \frac{\overline{w}\ell^2_{cr}}{8EI} &= \frac{1}{2R}\\[2em] \overline{V}\ell_{cr} - \frac{\overline{w}\ell^2_{cr}}{2} &= \frac{EI}{R}\end{aligned}\right\} = M$$

$$\overline{V}\ell_{cr} = \frac{3EI}{R}$$

$$\ell_{cr} = 2\sqrt{\frac{EI}{R\bar{w}}}$$

and $$\bar{V} = \frac{3}{2}\sqrt{\frac{EI\bar{w}}{R}}$$

But $\bar{V}$ is also the maximum shear

since $$\frac{1}{R_{min}} \approx \frac{13.3S_{max}}{h^2}$$

and $$\sqrt{\frac{1}{R}} = \frac{3.65}{h}\sqrt{S_{max}}$$

$$\ell_{cr(max)} = \frac{7.3}{h}\sqrt{\frac{EIS_{max}}{\bar{w}}}$$

and $$\bar{V}_{max} = \frac{5.5}{h}\sqrt{EI\bar{w}S_{max}}$$

The maximum moment will occur at a distance x from the free end where the shear = 0:

$$\bar{V} - \bar{w}x = \frac{3}{2}\sqrt{\frac{EI\bar{w}}{R}} - \bar{w}x = 0$$

$$x = \frac{3}{2}\sqrt{\frac{EI}{R\bar{w}}}$$

$$M = \bar{V}x - \frac{\bar{w}x^2}{2} = \frac{3}{2}\sqrt{\frac{EI\bar{w}}{R}} \cdot \frac{3}{2}\sqrt{\frac{EI}{R\bar{w}}} - \frac{\bar{w}}{2} \cdot \frac{9}{4} \cdot \frac{EI}{R\bar{w}} = \frac{9}{8}\frac{EI}{R}$$

$$M = 1.125\,\frac{EI}{R}$$

and $$M_{max} = \frac{15EIS_{max}}{h^2}$$

Note that the "beam action" associated with compressive strain is more critical than the "cantilever action" for tensile strain.

The critical length is underestimated by assuming an infinitely stiff foundation soil. Thus "flexible" foundations must have a length of <u>at least</u> $2\ell_{cr}$. From a practical point of view the determination of ℓ_{cr} is not very important, since foundation lengths less than those associated with flexible foundations produce lesser moments and shears.

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10. SUPPLEMENTARY NOTES

[ ] Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Criteria for site exploration, risk assessment, site development and housing construction in actual and potential mine subsidence areas are recommended. Appendix A includes guidance for subsidence profile determination and a proposed mathematical model which may aid in predicting complex subsidence patterns. Appendix B includes a commentary and proposed equations and procedures for the design of rigid and flexible foundations.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)
Design criteria; foundation design; geotechnical engineering; housing construction; mine subsidence; mining; settlement; structural design; structural engineering.

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