土的本构关系综述[1)]

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Ⅰ. 引　言

在目前计算机程序发展的情况下，不适当的材料模型（特别是对土这种材料来说）常常是限制应力分析能力的主要因素之一。由于土力学中一般采用的三轴应力条件下土的本构关系实际上并不存在，因此这种情况表现得更为明显。然而在近年来，提出了许多描述土的应力-应变和破坏性质的模型。所有这些模型当然都有各自的优缺点，这主要取决于它们的特殊用途。本文试图从一般土工问题和地震引起滑坡的数值分析的角度，来批判地评价土的现有本构关系和破坏准则，并试图确定它们的应用范围，相对的优缺点，以及对这些模型做进一步修正和改进的特殊需要。

更具体些来说，本文收入了土的现有一些应力-应变-强度模型，并就其在土坡的地震分析的应用方面进行评价。对这些模型的评价，考虑了以下三个方面：理论的可靠性；能够反映土的性质的主要特征；模型在有限元程序方面便于实现。本文的研究范围仅限于与时间无关的连续介质力学模型，特别是针对那些建立在弹性和塑性理论基础上的各种强度模型和变形模型。但是，本综述没有包括内时塑性模型。本文只作概括的评价。对本课题的更详细的讨论，见 Saleeb（1981），Chen & Saleeb（1982—1983）。

Ⅱ. 评价模型的标准

评价模型所使用的三条基本标准如下：①模型的理论评价，即关于连续介质力学基本原理的理论评价。主要是看它们是否满足连续性、稳定性和唯一性的理论要求。②模型的试验评价，就是看它们能否与各种试验资料很好符合，以及是否容易根据标准试验数据决定材料参数。③模型的数值和计算评价，就是指模型是否便于实现计算机计算。这里特别把重点放在提供非线性增量有限元计算机程序方面，以便求得不仅包括循环载荷，而且包括单调载荷的一般应力条件下滑坡问题的解。

总起来说，以上关于评价模型的标准，可以从连续介质力学方面看严格性要求，从实验方面看真正能代表土性的要求，以及从计算方面看使用简单的要求这三个方面来进行权衡。

Ⅲ. 强度模型

最为大家所知的土的材料性质，看来是破坏条件。有许多能够反映土的一些重要强度特性的破坏准则。Saleeb（1981）讨论过各种不同的强度准则。他将这些准则分为一参数模型和二参数模型。一参数模型包括 Tresca 准则，von Mises 准则和 Lade-Duncan 准则；二参数模型包括众所周知的 Mohr-Coulomb 准则，推广的 Tresca 模型和 Drucker-Prager 模

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1) 据 W. F. Chen（陈惠发）教授赠送译者的预印本译出。——译者

型，以及 Lade 二参数破坏模型．所有这些强度模型都采用了两个基本假设：各向同性和主应力空间的外凸性．引入第一个假设，主要是因为破坏模型常有的简单性．当然，某些粘土由于其不排水强度而存在着明显的各向异性，这就需要以六维应力空间破坏面的计算公式来代替三维主应力空间的相应公式．但是，对于许多土来说，各向同性的假设还是合理的．另一方面，外凸性的假设得到塑性力学中整体稳定性理论的支持．很明显，这种假设的可靠性还存在一些问题．事实上，有一些试验资料表明，在静水（侧限）压力的一个很大范围内，砂的破坏包络线对静水压力轴而言并非外凸的（Bishop 1972；Lee & Seed 1967）．

显然，土的抗剪强度随着有效平均法向应力而增加，所以一般不能用主应力空间中的柱体来描述，比如象一参数破坏模型中 von Mises 和 Tresca 模型的圆柱面和正六边形柱面就都是这种情况．只有在进行饱和不排水土的总应力（不是有效应力）分析时，才能使用 von Mises 模型和 Tresca 模型．

Lade-Duncan（1975）一参数模型对于无粘性土在一般的三维应力条件下是非常有效的．它既简单又包括了静水压力和中主应力的影响．

Mohr-Coulomb 准则对于均匀压力敏感的土来说，仍然不失为一个最好的破坏模型，但是由于它在三维空间中有尖角（奇点），因而在数学处理上不大方便．然而，可以借助于 Drucker-Prager（1952）圆锥体破坏面得到 Mohr-Coulomb 准则在三维情况下较好和光滑的一般型式．

Lade（1977）的二参数破坏模型是一种对于砂土和正常固结粘土来说在很宽的压力范围内都适用的模型．它考虑了子午面内破坏面轨迹的曲率，这就表明摩擦角随侧限压力的增加而减小．

Ⅳ．非线性弹性理论

1．*线性模型的修正*　各向同性材料的线弹性理论是模拟土的应力-应变性质的最简单和最古老的方法．因此合乎逻辑的结果看来是线性各向同性模型成为发展各种非线性土模型的基础．构成这类非线性模型的最简单方法，就是简单地将线性应力-应变关系中的弹性常数以取决于应力或/和应变不变量的割线模量来代替．这种类型的非线性模型，在 Boyce(1980)，Girijavallabhan & Reese（1968），Hardin & Drnevich（1972），Katona 等（1976）以及其他人的论文中都曾经讨论过．

这类模型在数学上和概念上都非常简单．它们考虑了非线性和静水应力影响这两个土的主要特性．

这类模型的主要缺点是它们仅描述与路径无关的性质，所以它们仅主要用于单调或比例加载的情况．而当其割线模量假设为任意函数时，不能保证能量函数 W 和 Ω 与路径无关，而且在某些应力循环中可能产生能量，这在物理上是不合理的．

2．*超弹性*　与上面提到的工程的和经验的方法相反，经典的超弹性理论是一种以土的割线应力-应变模型表示的更加合理的方法．其本构关系的基础是，假设存在着一个应变能函数 W 或一个辅助的能量函数 Ω，使得

$$\sigma_{ij}=\partial W/\partial\varepsilon_{ij},\quad 或\quad \varepsilon_{ij}=\partial\Omega/\partial\sigma_{ij} \tag{1}$$

作为超弹性模型的一个例子，是 Evans & Pister（1966）提出的三阶模型．此模型后来由 Ko & Masson（1976），Saleeb & Chen（1980）以及其他人在土力学中应用过．

超弹性模型对比例加载情况下土的应变情况相当精确．此外，在这种情况下使用这种模型，还能够满足连续介质力学中的连续性、稳定性、唯一性和能量考虑的严格要求．但是，超弹性类型模型不能确定土的变形的非弹性特点，在材料卸载时这一缺点就明显地表现出来．

超弹性模型的主要缺点是，它包括多个材料常数引起的复杂性．即使假设土为初始各向同性的，一个非线性超弹性模型也常常包含着过多的材料参数．例如，三阶超弹性模型需要9个常数，而四阶超弹性模型则需要14个常数．确定这些常数时一般需要做大量的试验，这就限制了这种模型的实际应用．

3．亚弹性　以上两类非线性弹性模型有一个明显的缺点，就是割线应力-应变关系中隐含着与路径无关的性质．一般情况下，这种与路径无关的性质对土来说是不正确的．亚弹性模型却能够进一步改进对土的性质的描述．它以材料特性模量作为应力和应变状态的函数，从而使增量应力和应变张量线性相关，例如

$$\dot{\sigma}_{ij}=C_{ijkl}(\sigma_{mn})\dot{\varepsilon}_{kl} \qquad (2)$$

在最简单的一类亚弹性模型中，增量应力-应变关系是以变切线模量来代替弹性常数而直接由各向同性线性弹性模型简单地推广而来的．其中变切线模量为应力或/和应变不变量的函数．这种方法曾经在许多岩土工程中普遍应用．在 Duncan 等（1970，1974，1978），Kondner（1963），Kulhawy 等（1969）以及其他人的论文中，都曾经讨论过这类简单的增量模型．

这类模型从计算和实用的观点来看是具有吸引力的．它们也容易实现有限元计算机程序的执行．模型中的材料参数能很容易地用明确规定的方法从实验室标准试验中测定，而且有许多参数已经积累了大量的数据．

在 Coon & Evans（1972），Desai（1980），Davis & Mullenger（1979）和 Tokuoka（1971）的论文中，都有这种一阶亚弹性模型基本公式和应用的实例．但是，又象超弹性模型那样，亚弹性模型的实际应用受到确定材料常数时所需要的试验的性质和数量的限制．没有确定这些材料常数的唯一方法．从 Saleeb（1981）的论文也可以看出，亚弹性模型的材料切线刚度矩阵一般是不对称的，这就大大增加了计算机储存和机时．而且，在这种情况下，一般不能保证边值问题解的唯一性．

Ⅴ．塑性变形理论

弹性模型与塑性模型间的基本差别，在于塑性理论处理加载与卸载情况时有所不同．这要靠引入加载函数的概念来完成．

土的变形基本上是非弹性的，因为载荷卸除后，卸载与加载形成的应力路径完全不同．如果用以上提到的任何一种弹性模型来描述土在一般的加载、卸载条件下的性状，那就还必须根据确定加载-卸载的准则来同时进行卸载处理．这种公式与塑性变形理论有密切的关系（Chen 1981）．在 Saleeb & Chen（1980）的论文中曾给出了这种塑性变形理论公式的实例．该文根据加载-卸载准则将三阶超弹性模型进行了扩充．对于增量应力-应变模型情况，广义的塑性变形理论就是目前众所周知的变模量模型（Nelson & Baron 1971；Nelson 等 1971，1977）．以弹性理论为基础的模型，在引进了加载准则之后，当在中性加载或接近中性加载时会产生连续性问题，而这正是所有弹性模型的一个共同缺点．

Ⅵ．弹塑性理论

对塑性流动理论来说，其增量应力-应变关系是根据以下三个基本假设建立起来的（Chen 1975，1980）：①存在着初始的和后继的屈服（加载）面 $f=0$；②描述逐渐扩大的后继加载面的硬化规律公式；③规定塑性应力-应变关系一般形式的流动法则．

对弹性-纯塑性模型来说没有硬化，因而所有后继屈服面与初始屈服面重合，且在应力空间中保持固定不动．

根据流动法则，塑性应变增量由下式给出：

$$\dot{\varepsilon}_{ij}^{p}=d\lambda\frac{\partial g}{\partial\sigma_{ij}} \tag{3}$$

式中 g 为塑性势函数，$d\lambda$ 为加载参量．当 $g\equiv f$ 时，方程（3）就是所谓的相适应流动（正交）法则；否则，就是不相适应流动法则．

弹性-纯塑性的 Drucker-Prager 模型，曾由 Chen（1975）和其他一些著作讨论和评价过．这类模型计算简单．在适当选取材料常数后，Drucker-Prager 准则可以同 Mohr-Coulomb 条件相一致（例如，在平面应变条件下给出相同的破坏载荷，Mizuno & Chen 1980）．这类模型反映了土的一些重要特性，如在低载荷下的弹性响应，接近破坏时材料刚度很小，破坏条件和屈服后的弹性卸载等．但是，这类模型的主要缺点是：由于使用了正交流动法则，结果过高地估计了屈服时的塑性剪胀性；在破坏面内不能描述滞回特性．这一类模型可以说是进行地震载荷下土坡渐进破坏分析的相当好的第一近似．至于帽子类的应变硬化模型，Dimaggio & Sandler（1971），Sandler 等（1976），Mizuno（1981）以及其他人都曾经讨论过．这类模型严格满足数学上稳定性、唯一性和连续性的要求．它们可以很好地与材料性质数据拟合，给出在静水压力的加载与卸载循环下的适当的压实，提供对塑性剪胀性的控制．当进一步采用运动硬化条件时，帽子模型可以预测不排水时低于破坏的循环剪切加载所产生的孔隙水压力增长．这一类模型能有效地用于地震载荷下土坡渐进破坏的分析．

Ⅶ．各种模型一览表

在结束本文时，将本研究的各种不同类模型的优缺点总括在表 1 — 4 中．表中仅给出其主要的优缺点；更详细的情况见 Saleeb（1981）的论文．

表 1　各种破坏模型优缺点一览表

类型	模型名称	优点	缺点
一参数模型	von Mises	①简单 ②破坏面光滑	①仅适用于饱和不排水土（总应力）
	Tresca	①简单	①仅适用于饱和不排水土（总应力） ②破坏面有尖角
	Lade-Duncan	①简单 ②考虑了中主应力影响 ③破坏面光滑	①仅适用于无粘性土

二参数模型	Mohr-Coulomb	①简单 ②对许多土都证明是有效的	①破坏面有尖角 ②忽略了中主应力的作用
	Drucker-Prager	①简单 ②破坏面光滑 ③适当选择参数后，能与 Mohr-Coulomb 准则吻合	①破坏面在偏平面上的轨迹为圆形与实验结果不一致
	Lade	①简单 ②破坏面光滑 ③子午线为曲线 ④较其他准则有更宽的压力适用范围	①仅适用于无粘性土[1]

1）应当是仅适用于砂土和正常固结粘土，不然与文中论述不符. ——译者

表 2　弹性类模型优缺点一览表

类　型	模型名称	优　　点	缺　　点
割线模型	修正线弹性	①概念上和数学上简单 ②常数易于测定，且许多参数已积累了大量数据	①变形的可逆性及与路径的无关性 ②体积特性与偏量特性不发生耦合 ③对于模量的任意函数，在某些应力循环下可能产生能量
	超弹性	①满足稳定性和唯一性要求 ②考虑了剪胀性和所有应力不变量的影响	①变形的可逆性及与路径的无关性 ②难以与试验拟合，且要做大量试验
切线模型	修正线弹性	①概念上和数学上简单 ②便于有限元计算 ③数据容易拟合 ④许多参数已有大量数据 ⑤已成功地用于许多实际问题	①变形增量的可逆性 ②体积特性与偏量特性不发生耦合 ③当采用 E_t，ν_t 时，不能恰当描述接近破坏时的性状 ④如果模量取为任意函数，则在某些应力循环下可能产生能量
	一阶亚弹性	①与应力路径有关 ②应力可导致各向异性	①变形增量的可逆性 ②切线刚度矩阵一般不对称，因此要求增加计算机储存和时间 ③资料难拟合，且需做大量试验 ④某些应力循环下可能产生能量 ⑤一般不能保证唯一性

表 3　塑性变形类模型的优缺点一览表

类　型	优　　点	缺　　点
塑性变形理论	①简单 ②允许滞回性状	①在中性或接近中性加载时发生连续性问题 ②除卸载情况外，性状与路径无关
变模量模型	①简单 ②数据能很好拟合 ③允许滞回性状 ④容易拟合 ⑤适用于有限元法计算	①在中性或接近中性加载时发生连续性问题

表 4　塑性类模型优缺点一览表

类　型	优　　点	缺　　点
Drucker-Prager 类纯塑性模型	①拟合简易 ②容易应用 ③适当选取参数后能与 Mohr-Coulomb 准则吻合 ④备有计算机程序 ⑤能用极限分析技术 ⑥满足唯一性要求（相适应流动法则）	①过高估计了屈服时的剪胀性 ②在破坏面内不能产生滞回性 ③不能推算不排水时低于破坏的循环剪切加载产生的孔隙水压力
帽子类硬化模型	①满足稳定性、唯一性及连续性等所有理论上的要求 ②能适当控制塑性剪胀性 ③静水压力加载和卸载循环过程中能产生滞回压密	①为拟合数据需进行试算 ②相当复杂 ③不能推算不排水时低于破坏的循环剪切加载所产生的孔隙水压力（当使用帽子运动硬化模型时就可以适当描述）

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•*应力加速腐蚀*　力学/化学问题的耦合在今天的部件中是一个重要的破坏机理。

•*设计力学的发展*　需要发展和利用有助于支持早期“范围外”设计阶段的变分法和定界方法。在这些方法中应特别努力将总系统中材料的选择和材料设计包括在内。

•*计算技术*　要求可靠的计算技术，它们能避免数值不稳定性，并能处理发生在实践中的热载荷和力学载荷的变化。

•*非金属系统*　需要有脆性材料的设计方法，以及需要研究材料的组合和分配。这种组合和分配将提高结构系统的运转性能和工作范围。

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（陳小芸　董务民校）

（上接第 185 页）这五章对传统意义下的断裂力学，从能量的观点给出了明晰的概括．虽然在推导应力强度因子时引用了一些弹性力学的结果，但这并未使能量方法失去完整性与严密性．后面三章是全书的重点，约占三分之二篇幅，介绍了前五章的内容在高聚物材料中的应用．第六章讨论十几种高聚物的起始扩展，包括高聚物低速实验中所遇到的几乎所有的现象．第七章研究高聚物起裂后缓慢的裂纹传播过程，并涉及粘弹性环境影响、疲劳和韧性撕裂等问题．第八章讨论高聚物中的冲击实验与动力效应问题．这三章提供了非常丰富的原始数据及其分析，并且大量的数据是第一次发表的．这些内容大都是 Williams 教授十几年来在英国帝国理工学院从事高聚物断裂力学的教学与研究中积累下来的第一手资料．这是本书的又一特点．

本书的第三个特点是对读者的数学要求并不很高，仅有微积分的基础就足够了．因此，本书较适合从事高聚物与复合材料方面的中、高级教学、工程科技人员参考，亦可作为有关专业研究生的教材．其中关于断裂力学基础理论分析部分，即使对断裂力学研究人员也很有启发性，并可作为理工科大学生学习断裂力学的一份很好的参考资料．

本书是 Ellis Horwood 机械工程丛书之一．作者 J.G.Williams 教授近年来在这一领域内享有很高的威望，是《International Journal of Fracture》，《Polymer》，《Journal of Material Science》等几家国际上影响较大的杂志的编委或审稿人．

最后应该指出，本书有一些印刷上的错误，读者在阅读时需加以注意．

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